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1 Study of D. C. Dynamo

2 Measurement of Resistance

3 Measurement of Shunt Field Resistance + Temp. Rise mean

4 Measurement of Armature Resistance

5 Starting a D. C. Shunt Wound Motor

6 Magnetization Curve of a Dynamo.

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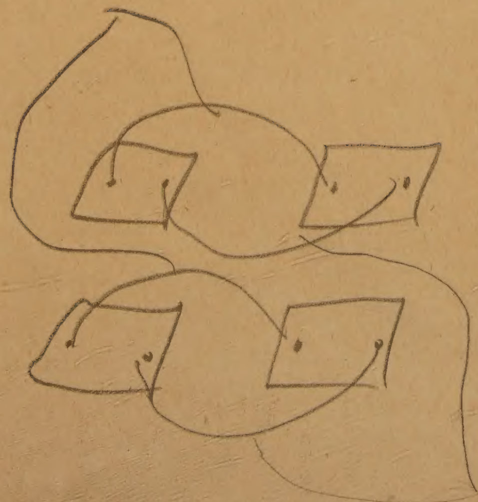

ENGINEERING SERIES

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ELECTRICAL ENGINEERING LABORATORY PRACTICE

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PREFACE

This book has been prepared to aid students in their electrical engineering power laboratory instruction. Both direct-current and alternating-current experiments are included in the one volume.

The authors have seen many problems arise in the laboratory, the answers to which cannot be found in the electrical-engineering textbooks commonly used. Such problems have received special emphasis.

The authors would appreciate having their attention called to any errors which may exist in this book.

Many helpful suggestions have been made by other members of the electrical-engineering staff at the University of Nebraska. The authors hereby express their deep appreciation of such help.

OSKAR E. EDISON
FERRIS W. NORRIS

UNIVERSITY OF NEBRASKA

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ELECTRICAL ENGINEERING LABORATORY PRACTICE

CHAPTER I

RESISTANCE OF CONDUCTORS

1. Measurements of resistances. Ohm's law, first announced in 1826, states that the ratio between the electromotive force E (or the difference of potential V) and the current I which flows, is a constant. In other words,

$$R = \frac{E}{I}, \tag{1}$$

where R is commonly called the resistance of the circuit, or

$$R = \frac{V}{I}, \tag{2}$$

where R is commonly called the resistance of that portion of the circuit across which the difference of potential is measured.

It is a fact that all conductors offer more or less resistance to the flow of an electric current, and experiment shows that for any particular conductor the resistance varies directly as its length and inversely as its area of cross section. This may be expressed in the form of an equation as follows:

$$R = \frac{\rho l}{a}, \tag{3}$$

where R = resistance of the conductor in ohms,
l = length of the conductor in feet,
a = area of cross section in circular mils, and
ρ = resistivity of the material (resistance of the material used per circular-mil foot, that is, the resistance of a conductor one foot long and having a cross-sectional area of one circular mil).

The constant ρ depends upon the kind of material used for the conductor as well as the temperature of the material. An approximate relation between resistivity ρ and temperature is

$$\rho = \rho_0(1 + \alpha_0 t), \tag{4}$$

where ρ_0 is the resistivity of the material at zero degrees centigrade and t is the temperature in degrees centigrade corresponding to the value ρ. The factor α_0 is a constant called the temperature coefficient, and is positive in some materials and negative in others.

The practical unit of resistance is called the ohm. The method of obtaining this unit has been established by international agreement. It is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass, of a constant cross-sectional area and of a length of 106.300 cm.

There are three common methods of measuring resistances in engineering practice:

1. The drop-of-potential method.
2. The series-voltmeter method.
3. The Wheatstone-bridge method.

2. Drop-of-potential method. This method is a simple application of Ohm's law. A known current I is passed through the resistance to be measured and the drop of potential V across the resistance is obtained. The resistance R is determined by calculating the ratio $\frac{V}{I}$.

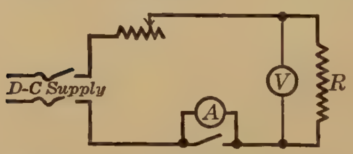

FIG. 1. Arrangement of instruments for measuring low resistances

There are errors introduced by this method of resistance measurement due to the fact that the ordinary voltmeter used will not have infinite resistance and the ammeter used will not have zero resistance. Therefore if the connections used are as in Fig. 1, the voltmeter will read the difference of potential across the resistance to be measured, and the ammeter will read the current in the voltmeter as well as the current in the resistance to be measured. The calculated resistance will be smaller than the actual resistance. If electrical connections are made as in Fig. 2, the ammeter will read the proper current

but the voltmeter will indicate too high a difference of potential due to the drop of potential across the ammeter. The calculated resistance will be higher than the actual resistance.

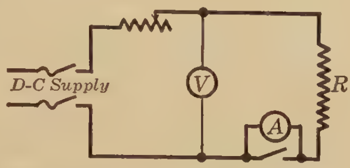

FIG. 2. Arrangement of instruments for measuring high resistances

The errors mentioned will be small if the connections shown in Fig. 1 are used for the measurement of small resistances and the connections shown in Fig. 2 are used for the measurement of large resistances. With the common range instruments used in electrical engineering laboratories, the connections shown in Fig. 1 should be used where the resistance is less than about 3 ohms, and the connections in Fig. 2 should be used when measuring larger resistances.

The above-mentioned errors can be easily eliminated if the resistance of the ammeter or the voltmeter is known.

EXPERIMENT 1–A

The Measurement of Resistance of Armatures and Fields by the Drop-of-Potential Method

Object. To measure the resistance of the armature, series field, shunt field, interpoles, brush contact, and armature leads of a dynamo.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. I, Exp. 1. The Macmillan Company.

Apparatus. A direct-current compound-wound motor or generator. Suitable rheostats for regulating the current.

Method. To measure the resistance of the armature circuit, connect the apparatus and instruments as shown in Fig. 1. Read the drop of potential between the following points: armature terminal to armature terminal, armature terminal to brush holder, brush holder to commutator bar immediately under the brush, between commutator bars immediately under brushes of opposite polarity. Repeat these observations for different values of current up to the rated current of the machine.

To measure the resistance of the shunt field, connect the apparatus and instruments as shown in Fig. 2. Take readings of the potential drop and current for different values of current.

Measure the resistances of the series field and the interpoles, using the proper connection of instruments. Take readings of potential drop and current, using several values of current up to the full-load rating of the machine.

Calculate the resistance in each case. Plot the drop of potential as ordinates against the current as abscissas. Plot the calculated resistance as ordinates against the current as abscissas.

Precautions. All ammeters should be protected by shunting switches. Never reverse nor disconnect voltmeter leads at the meter when the other ends of the leads are attached to live terminals. Always start with a sufficiently high range instrument so that it will not be damaged by excessive current or potential. Never leave a voltmeter permanently connected to a field circuit or any highly inductive circuit since the opening of the circuit may damage the instrument.

Questions. 1. Why are the resistances of the armature and the series field lower than the resistance of the shunt field?

2. What would be the values of the resistances in a machine twice as large but having the same voltage and speed ratings?

3. What would be the values of the resistances in a machine of the same size and speed but having a voltage rating twice that of the machine under test?

4. Why does the brush contact resistance vary with the current? (See § 55.)

5. How does the resistance of the ammeter or the current taken by the voltmeter introduce errors?

6. How can these errors be reduced?

3. The series-voltmeter method. This scheme is suitable for relatively high-resistance measurements. The diagram of connections is shown in Fig. 3.

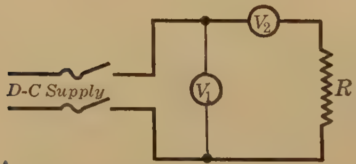

FIG. 3. Arrangement of instruments for measuring high resistances by the series-voltmeter method

The resistance of voltmeter No. 2 must be known. The current through the unknown resistance R can be readily calculated $\left(I_R = \frac{V_2}{R_2}\right)$, and the difference of potential across the unknown resistance will be the

difference between the two voltmeter readings. Thus the value of the unknown resistance equals

$$\frac{V_1 - V_2}{I_R} = \frac{V_1 - V_2}{\frac{V_2}{R_2}} = \frac{(V_1 - V_2)R_2}{V_2} = \left(\frac{V_1}{V_2} - 1\right)R_2, \qquad (5)$$

where R_2 = resistance of voltmeter No. 2.

The series-voltmeter method of measuring resistance is commonly used when it is desired to obtain the resistance of insulation.

EXAMPLE

The resistance of the insulation between an armature winding and the armature core is desired. Make the electrical connections as shown in Fig. 3. Assume that the voltmeter V_1 indicates 110 volts. $V_2 = 30$ volts. The resistance of the voltmeter $V_2 = 6000$ ohms.

The current passing from the armature windings through the insulation to the armature core will be $\frac{V_2}{R_2} = \frac{30}{6000} = 0.005$ amperes. The difference of potential across the insulation equals $110 - 30 = 80$ volts. Therefore the resistance of the insulation equals $\frac{80}{0.005} = 16{,}000$ ohms.

EXPERIMENT 1-B

The Measurement of High Resistance by the Series-Voltmeter Method

Object. To determine the value of several high-resistance units; also to measure the insulation resistance of a dynamo.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. I, Exp. 2.

Apparatus. Several resistors preferably ranging from 10,000 to 100,000 ohms. A dynamo whose insulation resistance can be tested.

Method. Connect the apparatus and instruments as shown in Fig. 3. It is preferable that the difference of potential used, should be from 500 to 600 volts and that the voltmeter have a high resistance and a full scale deflection of 600 volts. The resistance of the voltmeter must be known. If the supply difference of potential is steady, one voltmeter can be used for taking

both readings. A lower range voltmeter and a correspondingly lower source of potential can be used if 600 volts are not available. Take readings of the line difference of potential and the reading of the voltmeter when it is connected in series with the resistance to be measured.

Precautions. If using 500 or 600 volts, take such precautions as are necessary to avoid personal injury. Read Appendix A.

Questions. 1. Why is a 600-volt supply preferable to a 115-volt supply?

2. If a double-range voltmeter (0-300-600) is used, can the accuracy of the result be increased by using the lower range when placing the voltmeter in series with the resistance to be measured? Why?

3. Is there any danger in using the lower range?

4. The Wheatstone-bridge method. The diagram of connections shown in Fig. 4 represents the wiring for the Wheatstone-bridge method of measuring resistance. This is a zero, or balance, method in which the unknown resistance is compared to a standard resistance. This method of measuring resistance is used when great accuracy is desired.

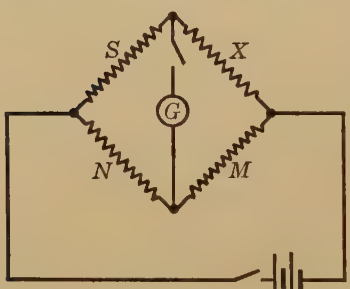

FIG. 4. Wheatstone bridge

The resistance S must be known. The ratio of the resistances M and N must be known. The galvanometer is connected as shown, and the values of S, N, and M are varied until the galvanometer shows no deflection when both switches are closed.

Then
$$X : S = M : N,$$
or
$$X = S \cdot \frac{M}{N}. \tag{6}$$

The greatest accuracy of measurement is obtained when X is nearly equal to S, and the resultant ratio of M to N is nearly equal to unity.

EXPERIMENT 1–C

The Measurement of Resistance by the Wheatstone-Bridge Method

Object. To study the principle of the Wheatstone bridge and to measure several unknown resistances by means of the bridge.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. I. John Wiley & Sons, Inc.

Apparatus. A Wheatstone bridge, preferably of the portable test-set type. Several unknown resistances to be measured. A battery and a galvanometer if these are not included in the test set.

Method. Study the construction of the bridge and make a diagram of the internal connections. Make the necessary connections and measure the unknown resistances. Repeat the measurements using different arrangements of the ratio arms.

Precautions. Take such precautions as are necessary to avoid damage to the galvanometer.

Question. What arrangement of ratio arms gives the greatest accuracy?

5. Variation of resistance with temperature. The resistance of most materials is affected by temperature. That of most metals increases as the temperature rises. The resistance of carbon falls very rapidly as the temperature rises. The resistances of liquids and most insulating materials also decrease as the temperature rises. This decrease is so marked in some insulating materials (such as glass, for instance) that they actually become conductors when they are heated to a red heat or when they are melted. The resistance of special alloys such as manganin remains approximately constant for all operating temperatures.

The resistance of most pure metals changes at approximately the same rate; that is, beginning at a temperature of zero degrees on the centigrade scale, the change of resistance is about 0.4 of 1 per cent per degree of the centigrade scale. This change per degree of the centigrade scale is called the temperature coefficient (α) of the material.

The effect of temperature on the resistance of a material may be expressed as follows:

$$R_t = R_0(1 + \alpha_0 t),$$

where R_t = resistance at t degrees centigrade,
R_0 = resistance at 0 degree centigrade,
t = temperature of material in degrees centigrade,
and α_0 = temperature coefficient at 0 degree centigrade.

For commercial aluminum* . . . . $\alpha_0 = 0.00423$
For commercial annealed copper . . . . . $\alpha_0 = 0.00427$
For commercial annealed iron . . . . . . $\alpha_0 = 0.005$
For German silver . . . . $\alpha_0 = 0.00031$
For manganin . . . . $\alpha_0 = 0.00001$

EXPERIMENT 1-D

Variation of Resistance with Changes in Temperature

Object. To observe the changes which take place in the resistance of a conductor when its temperature is changed.

Reference. Pender, "Handbook for Electrical Engineers."

Apparatus. A dynamo. Two thermometers. A short piece of iron wire. Carbon- and tungsten-filament incandescent lamps.

Method. Connect the field of the dynamo to a suitable source of power. Include in the connections a voltmeter and an ammeter so that the resistance of the field can be measured by the drop-of-potential method. Fasten a thermometer with its bulb against one of the field coils and cover the bulb with a small piece of putty. Use the second thermometer to read the room temperature. Take readings of the ammeter, voltmeter, and the two thermometers every fifteen minutes. Using the temperature coefficient of copper, calculate from the changes in resistance the average temperature of the coil. Plot the measured temperature and the temperature calculated from the resistance measurements as ordinates against time as abscissas.

Between readings, perform the following tests. Arrange a short piece of iron wire so that its resistance can be measured by the drop-of-potential method. Vary the current from a low value up to a sufficiently high value so that the wire will become

*Pender, "Handbook for Electrical Engineers." John Wiley & Sons, Inc.

dull red. Calculate the values of resistance and plot these as ordinates against the current as abscissas.

Perform similar experiments on the carbon- and the tungsten-filament lamps. Plot corresponding curves in each case and indicate on the curve sheets the color of the filament at the various values of current, thus: dull red, red, bright red, yellow, etc.

Questions. 1. Why does the measured temperature of the field coil differ from the calculated temperature?

2. Why are the curves plotted for the iron wire and for the two incandescent lamps not straight lines?

6. Specific resistance. The specific resistance (ρ), or the resistivity, of a material is the resistance of a circular-mil foot of the material. A circular-mil foot of material is a section of the material one foot long and having a uniform cross section of one circular mil.

A circular conductor has a cross section of one circular mil if the diameter is 0.001 inch, or 1 mil. The area of cross section of a circular conductor is m^2 circular mils, if the diameter of the conductor is m mils or $\frac{m}{1000}$ inches.

The resistance of a circular-mil foot of good commercial hard-drawn copper is very nearly 10.65 ohms at 20 degrees centigrade. The resistivity of aluminum is nearly twice that of copper, being 17.0 ohms at 20 degrees centigrade. The resistivity of iron and steel is about seven times that of copper.

The resistance of a wire or other piece of any particular conductor depends directly upon its length and inversely upon its cross section. So, if the resistance of a circular-mil foot of the wire (given in ohms) is multiplied by the total length in feet and divided by its cross section in circular mils, the result will be the resistance of the whole wire in ohms. This may be expressed as follows:

$$R = \frac{\rho l}{a},$$

where ρ is the resistivity of the material in ohms,
l is the length of the conductor in feet, and
a is the area of cross section in circular mils.

EXPERIMENT 1-E

The Determination of Specific Resistance

Object. To determine the specific resistance of several samples of wire.

References. Shepardson, "Elements of Electrical Engineering," Chap. XII. The Macmillan Company.

See also "Standard Handbook for Electrical Engineers." McGraw-Hill Book Company, Inc.

Apparatus. Several short lengths of wire of different materials and of different cross-sectional areas, preferably of the same length and mounted in some convenient manner. Micrometer calipers.

Method. Connect successive samples of wire in such a way as to be able to measure their resistances by the drop-of-potential method. Take readings of current and the potential drop for several values of current. Measure the diameters of the various wires by means of the micrometer calipers. Calculate the specific resistance of each wire used.

Precaution. Do not use currents large enough to appreciably heat the wire.

Questions. 1. How do the calculated specific resistances of the various materials tested compare with the values published in tables of specific resistances?

2. Show by example how to determine the circular-mil area of a rectangular conductor.

7. Wire gauges. Most wires for electric conductors, including most American copper wire and an increasing proportion of iron wire, are made according to the American wire gauge, abbreviated to A. W. G.

This gauge was proposed about 1855 by Brown and Sharpe, of Providence, R. I. This is a geometric series, having 0.460 in. as the diameter of No. 0000 wire for the first term, and 0.005 in. as the diameter of No. 36 wire for the fortieth term.

By letting the sizes 0, 00, 000, and 0000 be represented by the numbers 0, -1, -2, and -3 respectively, and denoting the gauge number of any wire by n, the diameter of any wire is

$$D_n = 0.460 \times 0.89053^{n+3} \text{ inches.}$$

By substituting $n+1$ for n in this expression, it may be shown that the diameter of any size is 1.12 times the diameter of the next size.

The area of a circular conductor in circular mils equals the square of the diameter expressed in mils. Therefore, the area of any particular size wire equals:

$$D_n^2 = 0.460^2 \times 1000^2 \times 0.89053^{2(n+3)} \text{ circular mils.}$$
$$D_n^2 = 211{,}600 \times 0.79305^{n+3} \text{ circular mils.}$$

Substituting $n+1$ for n in this expression shows that the area of any size wire is 1.26 times that of the next smaller size. The cube of 0.79305 is 0.49877, or almost 0.5, and therefore the area doubles or halves almost exactly every third size.

The weight as well as the area approximately doubles or halves each third number, and the safe carrying capacity approximately doubles or halves each fourth size number. The area and weight increase or decrease 26 per cent for each size number change. A wire ten sizes larger than another has ten times its weight and one tenth its resistance.

No. 10 copper wire has a diameter of about $\frac{1}{10}$ inch, has a resistance of about 1 ohm per 1000 feet, runs about 32 feet per pound or 32 pounds per 1000 feet, bare.

The approximate figures for No. 10 can be easily remembered, and the new values for any other size wire can be readily calculated.

EXAMPLES

1. To find the area, weight, and resistance of No. 13 wire. The area of cross section is approximately $10{,}000 \div 2 = 5000$ circular mils. The weight per 1000 feet is approximately $32 \div 2 = 16$ pounds. The resistance per 1000 feet is approximately $1 \times 2 = 2$ ohms.

2. To find the area, weight, and resistance of No. 4 wire. The area of cross section is approximately $10{,}000 \times 2 \times 2 = 40{,}000$ circular mils. The weight per 1000 feet is approximately $32 \times 2 \times 2 = 128$ pounds. The resistance per 1000 feet is approximately $1 \div (2 \times 2) = 0.25$ ohms.

3. To find the area, weight, and resistance of No. 2 wire. The area of cross section is approximately $10{,}000 \times 2 \times 2 \times 1.26 \times 1.26 = 63{,}500$ circular mils. The weight per 1000 feet is approximately $32 \times 2 \times 2 \times 1.26 \times 1.26 = 203$ pounds. The resistance per 1000 feet is approximately $1 \div (2 \times 2 \times 1.26 \times 1.26) = 0.157$ ohms.

4. To find the area, weight, and resistance of No. 20 wire. The area of cross section is approximately $10{,}000 \div 10 = 1000$ circular mils. The weight per 1000 feet is approximately $32 \div 10 = 3.2$ pounds. The resistance per 1000 feet is approximately $1 \times 10 = 10$ ohms.

8. Properties of copper wire. Copper is the most important metal for conductors of electricity. It may be soft-drawn or hard-drawn. Hard-drawn copper wire is made solely because it has a higher tensile strength than soft-drawn copper wire. The tensile strength of hard-drawn copper wire is from 40 to 70 per cent greater than that of soft-drawn copper wire, depending upon the size of the wire. The increase in strength is greater for the smaller wires. Soft-drawn copper wire is much easier to handle than hard-drawn copper wire, is less apt to break due to kinks, and has a lower specific resistance.

The properties of hard-drawn and soft-drawn copper wire are shown below.

Table I. Properties of Copper Wire

	Tensile Strength Pounds per Square Inch	Specific Resistance at 20 Degrees Centigrade
Hard-drawn wire	50,000 to 68,000	10.6
Soft-drawn wire	32,000 to 40,000	10.4

Copper is a non-magnetic metal and therefore the inductive reactance of copper wire is relatively small, independent of current, and directly proportional to frequency.

Copper, when exposed to ordinary air, becomes oxidized and turns to a black color. The coat is protective and the oxidizing process is not progressive as it is with iron and steel.

Properties of annealed copper wire are given in Appendix B.

9. Properties of aluminum wire. The use of aluminum for electric conductors is limited at the present time. Where economy of space is necessary it would never be used in place of copper, as, for instance, in armature windings.

Table II. Properties of Copper and Aluminum Wire

	Specific Gravity	Resistivity at 20 Degrees Centigrade	Tensile Strength	Elastic Limit
Copper	8.93	10.65 (hard-drawn)	60,000	30,000
Aluminum . .	2.68	17.0	24,000	14,000

The conductivity of a copper wire and an aluminum wire will be the same if the two wires bear the ratio of cross section $\frac{10.4}{17.0}$ (copper to aluminum), or 0.61.

The difference in area corresponds almost exactly to a change of two A. W. G. numbers. For example, a No. 10 copper wire may be replaced by a No. 8 aluminum wire, as far as conductivity is concerned.

For equal volumes, the weight ratio of copper to aluminum is $\frac{8.93}{2.68}$, or 3.33. For any given diameter the weight of aluminum wire is 0.3 of the weight of copper wire; or, for equal conductivities, the ratio of copper weight to aluminum weight $= \frac{8.93 \times 0.61}{2.68 \times 1.00} = 2.03$.

It will be noted that for equal conductivities the aluminum conductor has 1.64 times the cross section of the copper conductor. Therefore the problems of wind pressure, ice formation, and cost of insulation covering are more troublesome for aluminum than they are for copper. The saving in weight for equal conductivity is about 50 per cent if aluminum is used.

Stranded aluminum with a steel center is well suited for power transmission. The choice between aluminum and copper for power transmission is determined, very largely, by the market prices of the metals. The saving in weight for equal conductivity is about 27 per cent if steel-cored aluminum is used. Therefore, if steel-cored aluminum is used, it is possible to lessen strain upon towers, poles, insulator pins, etc., or to increase the distance between poles without increasing strains.

10. Properties of iron wire. Iron wire is used for electric conductors to a limited extent in telephone, telegraph, signal, and power work. It has certain properties which make it a very satisfactory conductor, but it also has serious faults.

The tensile strength of iron and steel is very much greater than that of copper or aluminum. Iron or steel is exceedingly cheap when compared with either copper or aluminum. The weight of iron is about 84 per cent of that of copper for equal volume. For equal conductivity iron wire will weigh from 5 to 6 times as much as copper and from 10 to 12 times as much as aluminum wire.

The most serious fault of iron for use as a conductor is that it is magnetic. The result is that with alternating currents the impedance may be increased several times over the ohmic resistance, depending upon the frequency of the current, the size of the conductor, etc.

When alternating current is used, the effective resistance of any conductor is increased due to skin effect and eddy-current loss within the conductor. Skin effect reduces the cross section of the conductor actually in use and therefore increases its resistance.

Skin effect is much more pronounced for iron conductors than it is for copper or aluminum conductors. This is due to the high permeability of iron. This effect can be minimized by stranding the conductors. Stranding the conductors also lowers eddy-current losses.

The resistivity ρ of iron or steel depends upon the size of wire, the frequency of the current, and the amount of current being carried.

If the cross section of the conductor is increased, ρ is increased.

An increase in frequency increases ρ. The increase is greater for the larger wires.

An increase in current causes an increase in ρ up to the condition of maximum permeability of the iron. As current is increased above this point, ρ decreases.

The hardness of iron has considerable influence on the tensile strength and the resistance of the metal. The tensile strength as well as the direct-current resistance increases as the hardness increases. The following information shows this to be true.

An iron conductor 259 mils in diameter, of the softest commercial grade (E. B. B.), will have an ultimate strength of 2400 pounds, and a direct-current resistance of 4.90 ohms. The same size wire, of the medium commercial hardness (B. B.), will have an ultimate strength of 2688 pounds and a resistance of 5.83 ohms. A steel wire of the same size will have an ultimate strength of 2880 pounds and a resistance of 6.77 ohms.

The electrical characteristics of iron and steel wire may be shown by the use of a few curves. T. A. Worcester gives the curves * for the use of iron wire shown in Figs. 5 to 8, inc.

* *General Electric Review*, Vol. 19 (1916), p. 488.

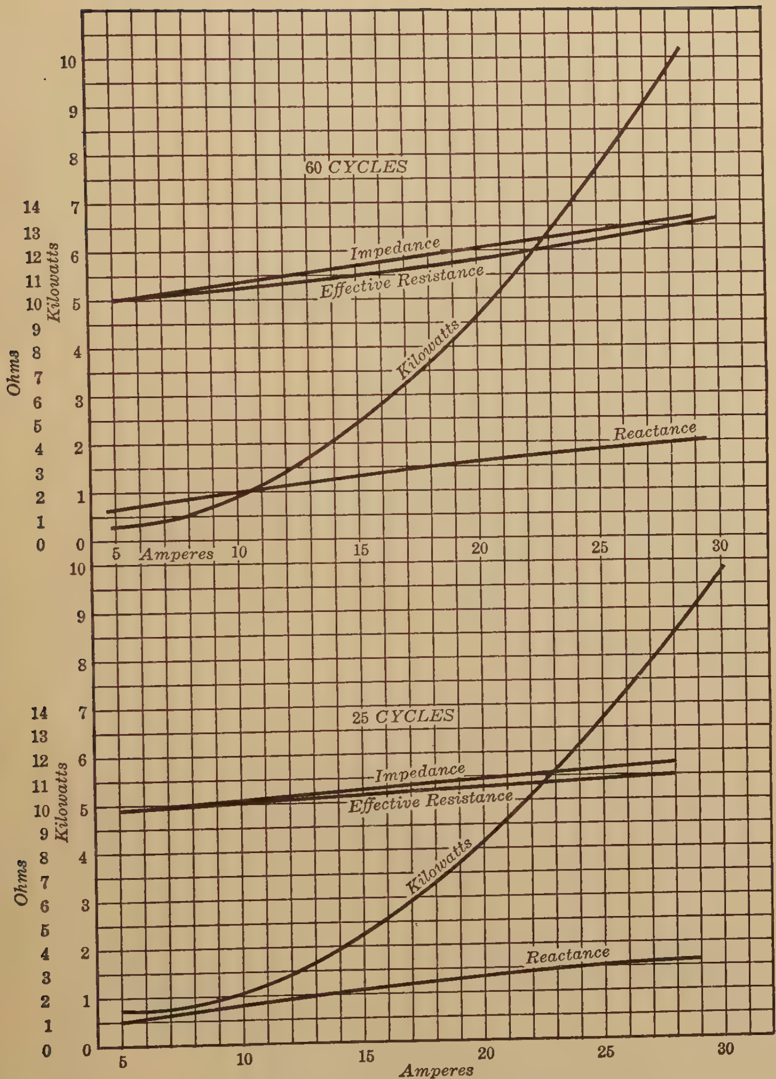

FIG. 5. Constants for one mile of $\frac{1}{4}$-inch galvanized stranded steel cable at 25 cycles and 60 cycles per second

Direct-current resistance per mile of cable is 9.72 ohms

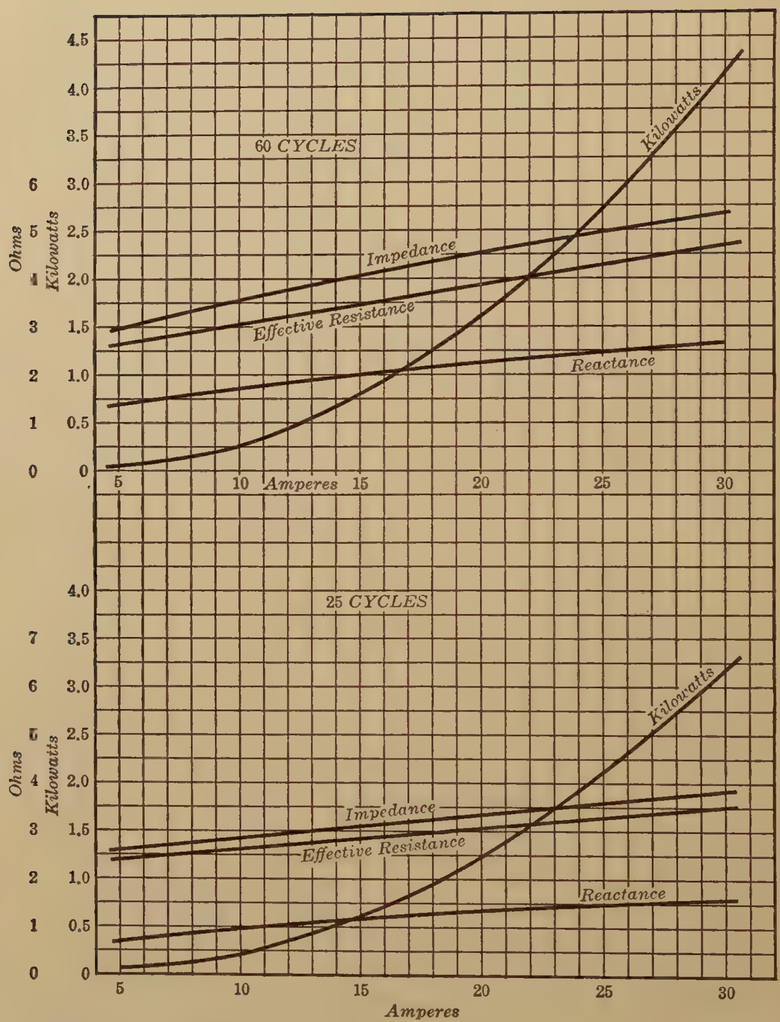

FIG. 6. Constants for one mile of $\frac{1}{2}$-inch galvanized stranded steel cable at 25 cycles and 60 cycles per second

Direct-current resistance per mile of cable is 2.42 ohms

11. Resistances in series and parallel. When two parts of an electric circuit are so connected that the entire current in the circuit passes through both parts, the parts are said to be connected in series. When two parts of an electrical circuit are so

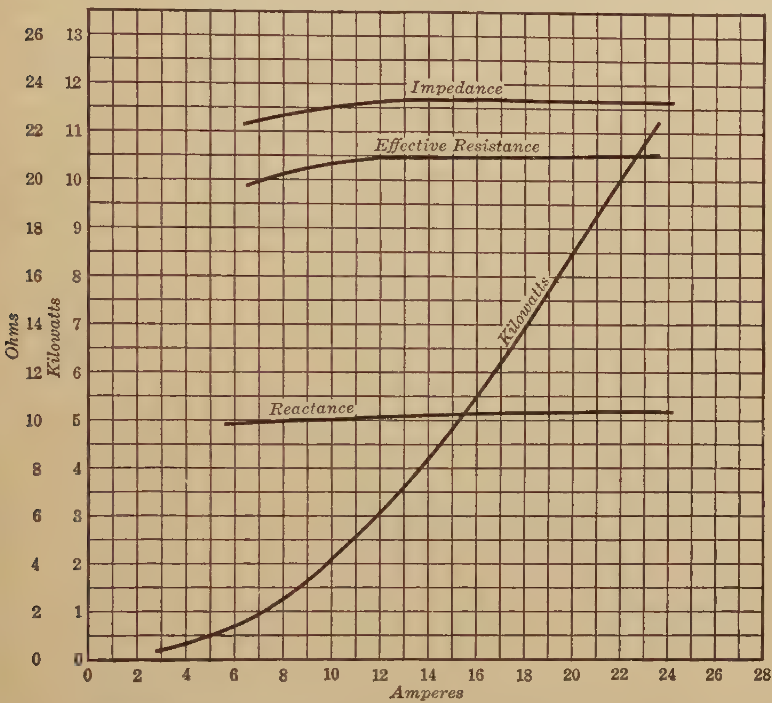

FIG. 7. Constants for one mile of No. 6 B. W. G. solid B. B. galvanized iron wire at 60 cycles per second

Direct-current resistance per mile of wire is 10.6 ohms. Tests made on three-phase circuits with wires at vertices of 84-inch equilateral triangle

connected that the current divides and a part of it flows through each part of the circuit, the parts are said to be in parallel.

The combined resistance of a number of resistances connected in series is equal to their sum.

The combined resistance of a number of resistances connected in parallel is equal to the reciprocal of the sum of the reciprocals of the individual resistances. Fig. 9 represents two resistances connected in parallel.

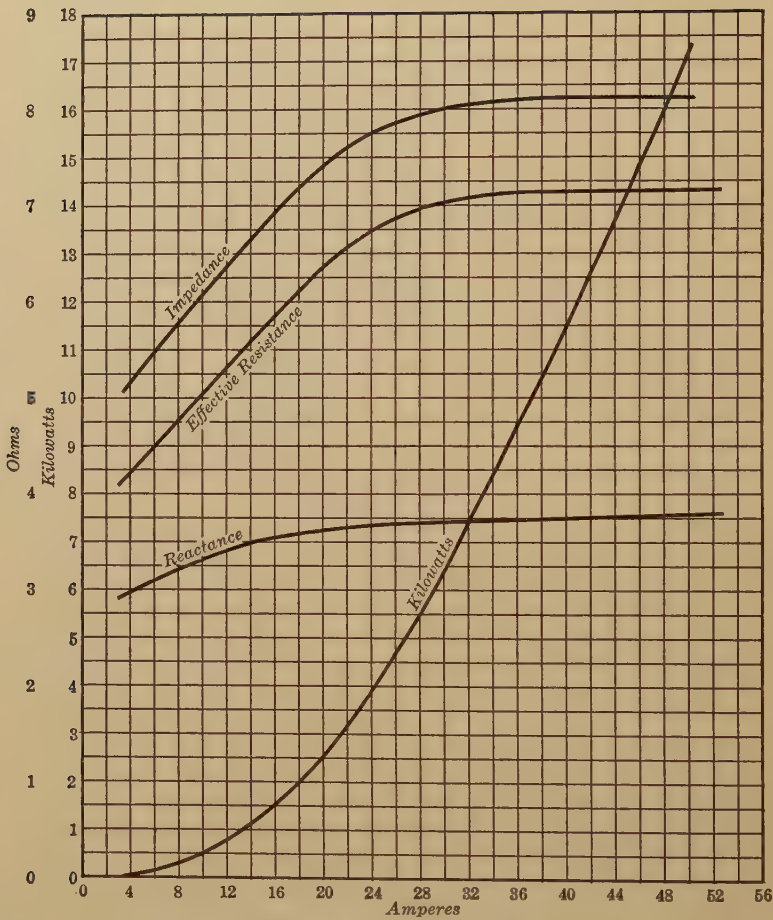

FIG. 8. Constants for one mile of $\frac{3}{8}$-inch galvanized stranded E. B. B. iron cable at 60 cycles per second

Direct-current resistance per mile of cable is 3.6 ohms. Tests made on a three-phase circuit with wires in one plane on 24-inch centers

The conductance of any part of an electrical circuit is the reciprocal of its resistance. The conductance of the top branch in Fig. 9 is $\frac{1}{R_1}$. The conductance of the bottom branch is $\frac{1}{R_2}$. The total conductance of the parallel combination is equal to the sum of the conductances. Therefore the total conductance of the combination is equal to $\frac{1}{R_1} + \frac{1}{R_2}$. The resistance of the combination is equal to the reciprocal of the total conductance. Therefore R (combination) equals

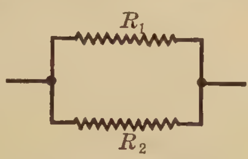

FIG. 9. Resistances in parallel

$$\frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}.$$

EXPERIMENT 1–F

A Study of Resistances in Series and Parallel

Object. To study experimentally the resulting resistance when several resistance units are connected in series, in parallel, or in various series-parallel combinations.

Reference. Cook, "Elements of Electrical Engineering," Chap. IV. John Wiley & Sons, Inc.

Apparatus. Several resistors.

Method. If the value of the resistance of each resistor is not known, determine it by any convenient method. Number the resistors and tabulate the resistance of each. Connect several resistors in series and measure their combined resistance. Connect them in parallel and measure their combined resistance. Try several series-parallel combinations and measure the resistance of each.

Precautions. Use connecting wires of very low resistance or make necessary corrections for their resistance. In measuring the resistance, do not use currents which appreciably heat the units.

Questions. 1. In each case, how does the measured result compare with the calculated result?

2. How do you explain any differences that exist?

12. Kirchhoff's laws. These two laws are deductions from Ohm's law and are especially useful in solving complex electrical circuit problems. They may be stated as follows:

First law. At any point in a circuit the sum of the currents flowing toward the point is equal to the sum of the currents flowing away from the point.

Second law. In any closed circuit the algebraic sum of the IR drops around any one path equals the algebraic sum of the e.m.f.'s in that path.

EXAMPLE

See Fig. 10. The arrows indicate the assumed positive directions of current.

Applying the first law to Fig. 10, we may write,

$$I_1 + I_2 + I_3 = 0.$$

Applying the second law to Fig. 10, we may write two equations as follows:

(Top loop) $\quad 110 - 5\,I_1 + 4\,I_2 = 0.$

(Bottom loop) $\quad -4\,I_2 + 2\,I_3 - 50 = 0.$

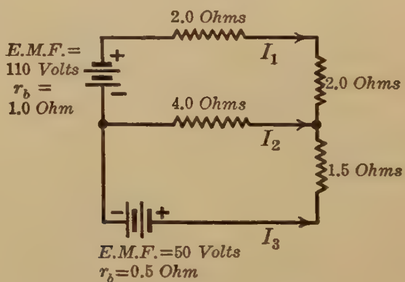

FIG. 10. Network of conductors

There are three unknowns and three independent equations. The problem can be readily solved.

EXPERIMENT 1–G

An Experimental Study of Kirchhoff's Laws

Object. To verify Kirchhoff's laws experimentally.

Reference. Christie, "Electrical Engineering," Chap. III. McGraw-Hill Book Company, Inc.

Apparatus. Several resistors such as used in Experiment 1-F. Two or more batteries, preferably portable storage batteries.

Method. Connect the resistors and the batteries into a sufficiently complicated network so that an application of Kirchhoff's laws is necessary for its solution. From known values of resistances and electromotive forces, calculate the current which should flow in each branch of the network. Insert ammeters and determine the actual current flowing. Compare the measured currents with the calculated values.

Precautions. Use sufficiently high resistances so that the resulting flow of current through the batteries will not produce an appreciable drop of potential, or measure the internal resistance of the batteries.

CHAPTER II

ELECTRICAL MEASURING INSTRUMENTS

13. Classification of instruments. There are several electrical phenomena which may be used for measuring electrical quantities such as current, difference of potential, etc. The more common of these are:

1. *Chemical*: electrolytic decomposition.
2. *Thermal*: heat produced by the passage of an electric current.
3. *Electrostatic*: the attraction or repulsion between two electric charges.
4. *Electromagnetic*: the interaction of two or more magnetic fields.

This classification is not complete, for there are several other electrical effects which may be used for making electrical measurements. These, however, are omitted since they are of little commercial value.

14. Chemical instruments. The chemical instruments are of no commercial value today but are of considerable historic interest. The international unit of current (ampere) is defined in terms of its chemical action. There have been on the market two types of chemical meters. In one, the quantity of electricity passing through the meter was measured by the volume of gas which was liberated from a specified acid solution. The second type consisted of two zinc plates in a cell filled with electrolyte. With the passage of electricity, zinc was transferred from the anode to the cathode. By weighing the cathode plate at the beginning and end of a period, its increase in weight could be used to determine the quantity of electricity which had passed the meter in that period. If this quantity of electricity was delivered at substantially a constant difference of potential, the energy consumption in watt hours could be determined by multiplying the quantity of electricity in ampere hours by the difference of potential in volts.

15. Thermal instruments. The thermal instruments are made in two forms. In the one case, the electromotive force produced

by a thermocouple, heated by the passage of current, is used as a measure of the current flowing. In the second form, called hot-wire instruments, a wire is heated by the passage of an electric current. The elongation of the wire, caused by the increased temperature, is used as a measurement of the current. Thermal instruments are of little value except in the measurement of high-frequency currents and consequently are of little use in the power laboratory.

16. Electrostatic instruments. The electrostatic instruments are built in many forms. The simplest and most common is the gold leaf electrometer. Electrostatic instruments are used almost entirely for measuring differences of potential, either in cases where a flow of current through the instrument would disturb circuit conditions or where the differences of potential are so great that they cannot be conveniently measured by other means. The electrostatic ground detector is a common commercial application of the electrostatic instrument. Since electrostatic instruments are of very little use in the electrical power laboratory, a more complete discussion of these instruments will not be attempted.

17. Electromagnetic instruments. Electromagnetic instruments depend for their operation upon the interaction of two or more magnetic fields. One of these fields is always the field produced by a current-bearing conductor, usually in the form of a coil. The other field, or fields, may be produced either by other current-bearing conductors or by permanent magnets. Electromagnetic instruments are subdivided into four groups: *galvanometers, dynamometers, induction type,* and *soft-iron type* of instruments.

18. Mechanical features. An electrical measuring instrument is of necessity a combination of electrical and mechanical parts. Consequently it is impossible to discuss the characteristics of any instrument without giving consideration to its mechanical construction as well as to its electrical circuits. All or nearly all electromagnetic instruments have certain common mechanical features. They have a moving element, actuated by the electromagnetic forces produced, and held back by some restraining force. It is of importance that the friction of this moving element be reduced to a minimum. This is usually accomplished by pivoting the moving element in jeweled bearings. In order

to reduce the frictional torque as much as possible, the pivots are usually made with a very small diameter. For indicating instruments this diameter is usually in the order of 0.0005 inch. The supporting of the moving element on so small an area gives rise to bearing pressures in the neighborhood of ten tons per square inch. In order that a bearing may have reasonably long life under such enormous bearing pressures, it is necessary that the bearing materials be of great hardness. The pivot is made of a very hard steel, so hard, in fact, that it can be driven into a pair of lineman's pliers without blunting the point. This pivot rests in a jeweled cup which is much harder than the pivot itself. Consequently, when for any reason the bearing pressure becomes excessive, the pivot is usually damaged rather than the jewel. Great care should, therefore, be taken to avoid any treatment of the instrument which will abnormally increase the already high bearing pressure, thereby blunting the pivot and causing undue friction in the instrument. Such excessive pressure may be caused by jarring the instrument severely or by so adjusting the jewels that both of them are in contact with the pivots at the same time. The upper jewel should act merely as a guide bearing.

19. Restraining forces. The force produced in any electromagnetic instrument is either opposed by a conservative restraining or by a dissipative restraining force. A conservative restraining force returns the moving element to zero after the deflecting force has been removed. A dissipative restraining force limits the rate of motion, but has no tendency to return the moving element to zero after the force which produces motion has ceased. A few special instruments employ no restraining force whatsoever, but can come to rest in any position and are free to move with no opposition except the inertia of the moving element. Instruments having conservative restraining forces are usually spoken of as "indicating instruments" while instruments having dissipative restraining forces are called "integrating instruments" because their reading is directly proportional to the time during which the force acts.

A conservative restraining force usually consists of two hairsprings coiled in opposite directions. By coiling them in opposite directions it is found that the zero adjustment is not affected by temperature change. Also, if the moving element consists

of a coil, the hairsprings are used as a means of conducting current to and away from the coil. Consequently, there is often a double duty imposed upon the springs. They must have good elastic characteristics and at the same time have sufficiently high conductance so as not to impose too much resistance in series with the moving coil. The springs should have sufficiently low elastic hysteresis so that after the deflecting force has been removed, the needle will immediately return to zero within an amount too small to be noticed by the naked eye.

A dissipative restraining force usually consists of some metallic disc or cylinder moving between the poles of one or more permanent magnets. The disc or cylinder was formerly made of copper, but is now almost always made of aluminum since the reduction in weight relieves the bearing of unnecessary pressure. Such a dissipative restraining force is in reality a small generator. Whenever a motion of the aluminum disc or cylinder takes place through the magnetic field of the permanent magnets there are induced, in the aluminum, electromotive forces and consequently eddy currents which react with the field and oppose the motion of the disc through the field. Since the field is of constant value, being produced by the permanent magnets, the induced electromotive force, and consequently the eddy currents, will be directly proportional to the rate of motion of the disc through the field. This results in a retarding force which is directly proportional to the velocity of the disc.

20. Instrument accuracy. The common method of expressing the accuracy of indicating instruments is to state that the instrument is correct to within a given percentage of full-scale value, and that this applies throughout the scale. In other words, the absolute error does not exceed a certain value at any point on the working part of the scale.

The limit of accuracy attainable in the best grades of galvanometer and dynamometer instruments is 0.1 per cent of full-scale value. The limit of accuracy attainable in the best grades of portable galvanometer and dynamometer instruments is 0.25 per cent. Portable soft-iron instruments are usually accurate to within 0.5 per cent. Small portable instruments and switchboard instruments are usually accurate to within 1.0 per cent.

21. Galvanometers. Galvanometers consist of a permanent magnet and a current-bearing conductor. If the permanent mag-

net is small and pivoted in the field of a large fixed coil, the instrument is known as a tangent galvanometer. On the other hand, if the current-bearing conductor, in the shape of a coil, is light and pivoted in the field of a permanent magnet, the instrument is known as a D'Arsonval galvanometer. The tangent galvanometer has several serious disadvantages and consequently is little used today. The force acting between the movable magnet and the field of the fixed coil is a maximum when the two magnetic fields are at right angles to each other. As the permanent magnet rotates from this position the force acting is reduced by the cosine of the angle of displacement. Consequently the scale of a tangent-galvanometer type of instrument cannot be uniform. The major portion of the magnetic circuit consists of air, thus resulting in low flux densities and small torque. In the D'Arsonval galvanometer these difficulties have been largely overcome. In the first place, the permanent magnet is fitted with pole shoes, so shaped that a cylindrical opening is formed. In this opening is placed a concentric cylindrical piece of soft iron, thus leaving an air gap of uniform depth between the pole shoes and this core. The movable coil is pivoted so that its two edges move in this air gap. Consequently the movable coil is always moving at right angles to a uniform magnetic field. Therefore the torque acting will be directly proportional to the current flowing in the movable coil and independent of the angular position of the coil. Since the deformation of the springs is proportional to the force acting, the scale will be uniform except for any imperfections which may arise in the process of manufacturing. Since the magnetic circuit is through iron except for the two small air gaps, the flux density will be relatively high; therefore the ratio of torque to weight of the moving element will be much higher than in the tangent galvanometer. Although every D'Arsonval galvanometer has a nearly uniform scale, a uniform scale on an instrument is not proof that the instrument is of the D'Arsonval galvanometer type, for there are several other instruments which also have nearly uniform scales.

The D'Arsonval galvanometer can be used as either an ammeter or a voltmeter. The instrument is inherently an ammeter since the deflection is directly proportional to the current flowing in the movable coil. In order to have a sensitive and durable

instrument it is necessary to make the movable coil light in weight, consequently it must be made of fine wire. In order to measure currents larger than those which can be passed directly through the movable coil it becomes necessary to shunt the movable coil with a fixed resistance so that only a definite portion of the total current passes through the coil. This shunt should be of such material as to have a negligible temperature coefficient at all ordinary temperatures. If the moving coil is placed in series with a high resistance the current flowing will be directly proportional to the difference of potential impressed across this series combination. Consequently the instrument becomes a voltmeter. The resistance placed in series with the movable coil is called a multiplier and should be of such material as to have a low temperature coefficient. The shunt or the multiplier may be placed in the same box as the moving element or it may be separate from the moving element, depending upon which is the more convenient. When the ammeter shunt is separate from the moving element it is necessary to connect the moving element to the shunt by means of leads having a definite resistance in order to have the proper current division between the shunt and the moving coil.

The D'Arsonval galvanometer is sometimes used with a dissipative restraining force in place of the conservative restraining force, that is, the hairsprings are replaced by an aluminum disc rotating between the poles of one or more permanent magnets. In this case the single coil is replaced by several coils connected in a way similar to the armature winding of the ordinary direct-current dynamo. A commutator and brushes are used for carrying the current to and away from the moving element. This constitutes a direct-current motor having constant flux, since the field is produced by a permanent magnet. Therefore the torque tending to produce rotation is directly proportional to the current flowing in the armature. Since the dissipative restraining force causes a countertorque which is directly proportional to the velocity of the moving element, the armature will attain a speed proportional to the current flowing. The number of revolutions, therefore, becomes a measure of the product of current multiplied by time, or the quantity of electricity which has passed through the meter. By suitable gears and dials the instrument can be made to read either in coulombs

or in ampere hours, the latter being the common commercial unit. Thus a D'Arsonval galvanometer arranged for continuous rotation and equipped with a dissipative restraining force becomes an ampere-hour meter. Such a meter finds considerable commercial use in connection with storage batteries as an indication of their state of charge or discharge.

EXPERIMENT 2-A

The Study and Calibration of a D'Arsonval-Galvanometer Voltmeter

Object. To study the mechanical construction and to calibrate a D'Arsonval-galvanometer-type voltmeter by comparing its readings with those of a standard voltmeter.

Reference. Laws, "Electrical Measurement," Chap. V. McGraw-Hill Book Company, Inc.

Apparatus. A D'Arsonval-galvanometer type of voltmeter to be calibrated. A standard voltmeter. A potentiometer rheostat or potential divider for varying the difference of potential impressed across the voltmeters.

Method. Study the mechanical construction of the voltmeter, noting in particular the method of supporting the permanent magnet, the pole pieces, and the soft-iron cylindrical core. Note the method of attaching the hairsprings and the provisions made for setting the pointer on zero. Note the uniformity or lack of uniformity of the scale and explain the reasons for same. Place the voltmeter being studied in parallel with the standard voltmeter and take simultaneous readings of the two instruments for different values of potential from zero to full-scale deflection. Repeat, using decreasing values of potential difference.

Precautions. While taking readings for increasing differences of potential be careful not to raise the impressed difference of potential too rapidly or to exceed the desired value. Use similar precautions in taking readings for decreasing values of potential. If the difference of potential of the supply is much greater than the range of the voltmeter, it is possible to damage an instrument seriously by accidentally impressing on it a potential considerably in excess of rated full-scale deflection.

Curves. Plot the correction curves for both increasing and decreasing differences of potential, using corrections as ordinates and instrument readings as abscissas.

Questions. 1. What might cause ascending and descending readings to differ?

2. If a potentiometer (three-point) rheostat were not available what other means of obtaining suitable variations could be used?

EXPERIMENT 2-B

The Study and Calibration of a D'Arsonval-Galvanometer Ammeter

Object. To study the mechanical construction and to calibrate a D'Arsonval-galvanometer-type ammeter by comparing its readings with those of a standard ammeter.

Reference. Laws, "Electrical Measurements," Chap. I.

Apparatus. A D'Arsonval-galvanometer-type ammeter to be calibrated. A standard ammeter. A suitable current-limiting rheostat for regulating the current flowing through the ammeters.

Method. Study the mechanical construction of the ammeter. If Experiment 2-A has already been performed compare the moving element of this ammeter with the moving element of the voltmeter previously studied. Examine the construction of the shunt and method of connecting the shunt to the moving element. Check the scale with a pair of dividers in order to see if it is uniform throughout its length. Place the ammeter being studied, in series with the standard ammeter and take simultaneous readings of the two instruments for different values of current from zero to full-scale deflection.

Curves. Plot the correction curve for the ammeter, using corrections as ordinates and instrument readings as abscissas.

Questions. 1. What are the relative advantages of separate and self-contained shunts?

2. What materials are suitable for use as shunts?

3. What would be the effect of making a shunt of iron?

4. What would be the result of increasing the length of leads connecting the shunt to the millivoltmeter?

22. Dynamometers. The electrodynamometer differs from the galvanometer in that the permanent magnet is replaced by a current-bearing conductor usually in the form of one or more coils. Thus dynamometer instruments are distinguished from all other types of instruments in that there are at least two current-bearing coils. Of these coils at least one must be fixed and at least one movable. Usually the fixed coil is divided into two parts having magnetomotive forces in the same direction. These two parts are separated by a sufficient distance to allow the pivoting of the movable coil between the two parts of the stationary coil. Thus the movable coil is placed in the magnetic field of the stationary coil and consequently a certain torque is produced depending upon the strength of the magnetic field, the current flowing in the movable coil, and the angular position of the movable coil.

The dynamometer type of instrument lends itself readily to a great variety of uses. It can be used as a voltmeter, ammeter, wattmeter, watt-hour meter, power-factor indicator, etc. If the stationary and movable coils are connected in series and in turn connected in series with a high noninductive resistance, and if the torque produced is opposed by a conservative restraining force, the instrument becomes a voltmeter. The dynamometer-type voltmeter has one inherent error which cannot be completely overcome, but which can in general be reduced to a negligible amount. The fixed and movable coils are, of necessity, inductive, and consequently the impedance of the voltmeter consists in part of inductive reactance. Therefore the current flowing will be a function of the frequency. This, of course, is highly undesirable since the meter could read correctly at only one frequency. If the inductive reactance of the coils is made small compared to the resistance of the series multiplier, then the current flowing will be limited mainly by the resistance of the meter, and consequently will be almost independent of the frequency. Thus the error introduced can be made negligibly small for all ordinary frequencies, but at high frequencies, such as radio frequencies, this error becomes excessive and the meter becomes useless for this type of work. If iron is placed in the magnetic circuit of a dynamometer-type meter, it will be accurate only at the frequency for which it is calibrated. Consequently iron is seldom used in this type of meter.

The dynamometer-type instrument can also be used as an ammeter. Since the moving coil is similar to the moving coil of a galvanometer it can carry only a very small current. Consequently for measuring larger currents it becomes necessary to shunt the movable coil. Since the movable coil contains both resistance and inductive reactance, it becomes necessary to have an inductive shunt. The ratio of the shunt resistance to the resistance of the movable coil must be the same as the ratio of the inductance of the shunt to the inductance of the movable coil. Therefore, in building a shunt for use in an alternating-current circuit, it is necessary to adjust both its resistance and its inductance. When these ratios are equal a certain part of the total current will always pass through the moving coil independent of the frequency of the circuit. The stationary coil is similar to that in the voltmeter except that it consists of only a few turns of heavy wire. This is connected in series with the above shunt and carries the total current to be measured. Due to the difficulty of manufacture, shunts are very seldom used in alternating-current instruments, and the dynamometer type of ammeter is not a common instrument.

In both the dynamometer voltmeter and ammeter the torque acting is proportional to the product of the field strength and the current in the moving coil. But since the current in the movable coil is the same as, or a definite proportion of, the current in the fixed coil, the torque becomes proportional to the square of the current flowing. In the case of the voltmeter it is also proportional to the square of the terminal difference of potential. Since the moving element has considerable mass, it will not follow the rapid variations in torque but will assume a constant deflection equal to the average torque acting. By placing a square-root scale on the meter it will read the square root of the average squared instantaneous values of current. This reading is called the "effective value," "root-mean-square value," or "virtual value." Since the movable coil does not always maintain the same relative position to the fixed coil, the conditions are somewhat more complicated. The maximum torque occurs when the axis of the movable coil is at right angles to the axis of the fixed coil. In any other position the torque is reduced by the cosine of the angle of displacement. Therefore in the actual instrument the scale may depart materially from

a strictly square-root scale. Very often the upper end of the scale is crowded due to the fact that the angle of displacement is approaching ninety degrees and, consequently, the cosine is approaching zero.

The dynamometer type of instrument lends itself particularly well for use as a wattmeter. As a wattmeter it consists of a fixed coil similar to the fixed coil of the dynamometer-type ammeter and a movable coil similar to the movable coil of the dynamometer-type voltmeter. By placing the stationary coil in series with the load to be measured and having a magnetic circuit of air, the flux produced will be directly proportional to the current flowing. By placing the movable coil in series with a high resistance multiplier across the difference of potential supplied to the load, the current in this coil will be directly proportional to the difference of potential. Therefore the instantaneous torque acting is proportional to the product of the instantaneous current and the instantaneous difference of potential. Since the moving element has considerable inertia, it will not follow the rapid variations of instantaneous power but will assume a steady deflection proportional to the average torque acting. Therefore the instrument reads the average power supplied to the load.

If in the above instrument the conservative restraining force is replaced by a dissipative restraining force, the instrument becomes a watt-hour meter. The single moving coil of the wattmeter must, of course, be replaced by an armature and commutator so as to allow continuous rotation to take place. In this instrument, as in the dynamometer wattmeter, the torque acting is proportional to the product of instantaneous current and instantaneous difference of potential. By using a dissipative restraining force, the number of revolutions made by the meter will be proportional to the average power supplied to the load multiplied by the time during which this power is being supplied. The meter can therefore be calibrated to read in watt-hours or, as is usually the case, in kilowatt-hours. This meter will operate on either alternating- or direct-current circuits providing the resistance in series with the movable coil is made noninductive.

There are several other possible uses for the dynamometer-type of instrument construction, but the above examples will serve to illustrate the possibilities of this type of instrument.

23. Compensation of the dynamometer-type wattmeter. If the potential coil of a dynamometer wattmeter is connected to the load side of the current coil as shown in Fig. 11, then the current taken by the potential coil will flow through the current coil and the wattmeter will read the loss in its own potential circuit. On the other hand, if the potential coil is connected to the line side of the current coil, then the difference of potential across the potential circuit of the wattmeter will be the difference of potential across the load plus the IZ drop in the current coil, and the wattmeter will read the loss in its own current coil. Consequently, in low-capacity wattmeters, it is customary to wind a compensating coil on top of the current coil. This compensating coil consists of the same number of turns as the current coil. It is connected in the circuit as shown in Fig. 12. When thus connected, the current taken by the potential coil will flow through the compensating coil in one direction and through the current coil in the opposite direction. When the load is zero, the magnetomotive force of the compensating coil will be equal and opposite to the magnetomotive force of the current coil, and consequently no flux will be produced and the meter will not read any of its own losses. Some means of using the meter without the compensating coil is always provided, because in certain work more accurate readings are obtained without the use of the compensating coil. The potential terminal next to the compensating coil always carries a polarity marking. Only a minimum of insulation is used between the compensating coil and the current coil in order to prevent magnetic leakage between these

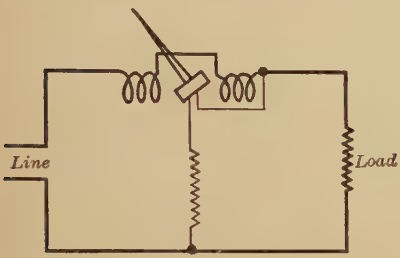

FIG. 11. Dynamometer-type wattmeter

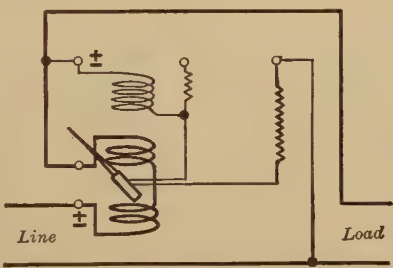

FIG. 12. Compensated dynamometer-type wattmeter

two coils. It is therefore undesirable ever to have any appreciable difference of potential between the compensating coil and the current coil. Such difference of potential can be avoided by always connecting that terminal of the potential coil having the polarity marking to the load side of the current coil. If with this connection the wattmeter is found to read backward, always reverse the current coil and not the potential coil.

24. Compensation of the dynamometer type of watt-hour meter. In the dynamometer type of watt-hour meter a certain amount of friction is unavoidable. This friction is due to the bearings, the commutator, and the recording dials. As a result rotation will not begin until an appreciable load current is flowing through the current coil of the meter. In order to make the meter more sensitive to light loads, a compensating coil is placed in series with the potential coil and so arranged that its magnetomotive force adds to the magnetomotive force of the current coil. Thus a small amount of flux will be produced even when the load is zero. The compensating coil is made adjustable so that this no-load flux can be made almost sufficient to produce a torque to balance the frictional torque in the meter. Therefore, even a small load current will produce sufficient increase in torque to start the meter rotating. The arrangement of the compensating coil is shown in Fig. 13. It will be noticed that the purpose of compensation in the watt-hour meter is entirely different from that in the wattmeter and care should be taken not to confuse them.

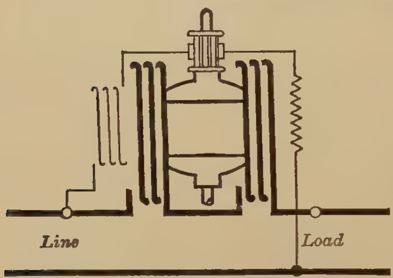

FIG. 13. Dynamometer-type watt-hour meter

EXPERIMENT 2–C

The Study and Calibration of a Dynamometer-Type Wattmeter

Object. To study the mechanical construction of a dynamometer-type wattmeter, to calibrate by comparing its readings with the product of the readings of a standard ammeter and

voltmeter, and to note the effect of stray external fields upon the indications of the instrument.

Reference. Laws, "Electrical Measurements," Chap. VI.

Apparatus. A dynamometer-type wattmeter, not magnetically shielded. A standard ammeter and voltmeter. A suitable current-limiting rheostat for use as a load. A potentiometer rheostat. A source of direct-current supply.

Method. Connect the instruments as indicated in Fig. 14. Take a set of readings at constant potential, varying the current from zero to the rated current capacity of the wattmeter. Reverse the polarity of the supply leads and repeat the above readings. Take a third set of readings, maintaining constant current at or near the current rating of the wattmeter and vary the impressed difference of potential from zero to the potential rating of the wattmeter. Again reverse the polarity of the supply leads and repeat the above readings. With rated potential impressed upon the potential coil of the wattmeter and a low value of load current, rotate the instrument about a vertical axis and note the reading of the instrument for the various positions in which it is placed.

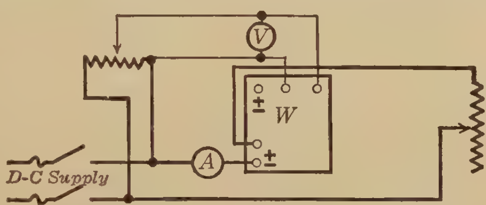

FIG. 14. Diagram of connections for testing a dynamometer-type wattmeter

Curves. Plot the various correction curves for the instrument, using correction in watts as ordinates and the independent variable as abscissas.

Questions. 1. Why should the reversal of both current and potential coils of the wattmeter affect the error of the instrument?

2. How can errors due to this cause be eliminated?

3. Why should the position of the wattmeter affect the zero reading of the instrument?

4. Will these errors be present if the instrument is used in an alternating-current circuit?

5. What will such an instrument read when used in an alternating-current circuit?

EXPERIMENT 2-D

The Study and Calibration of a Dynamometer-Type Watt-Hour Meter

Object. To study the mechanical construction of a dynamometer-type watt-hour meter, and to calibrate it by comparing its readings with the product of the readings of a standard ammeter, voltmeter, and stop watch.

References. Jansky, "Electrical Meters," Chap. XIII; McGraw-Hill Book Company, Inc.

National Electric Light Association, "Electrical Meterman's Handbook."

Apparatus. A dynamometer-type watt-hour meter. A standard ammeter and voltmeter. A stop watch. A suitable current-limiting rheostat for use as a load. A source of direct-current supply.

Method. Connect the ammeter in series with the current coil of the watt-hour meter, and connect the voltmeter in parallel with the potential coil of the watt-hour meter. For different values of load current take readings of the time required for the watt-hour meter to make a certain number of revolutions. Also take readings of the difference of potential and current during this interval of time. Adjust the meter by moving the permanent magnets in or out as required so that it will read correctly at rated load. Adjust the meter by adjusting its compensating coil so that it will read correctly at one-tenth of its rated load. After making the above adjustments take another complete set of readings so that the correction curve can be plotted from zero to 150 per cent of rated full load.

Curves. Plot the correction curve as obtained before adjusting the meter and also the correction curve obtained after adjusting the meter, using per-cent registration as ordinates and per-cent rated current as abscissas.

Questions. 1. How is the light-load adjustment of this type of meter affected by a change in line voltage?

2. How is the accuracy of this type of meter affected by changes in temperature?

3. Should the potential circuit be connected to the line side or the load side of the current coil? Why?

25. Induction instruments. The induction type of instrument might be considered as a special case of the dynamometer type. But since it differs from the dynamometer radically in mechanical construction it is here placed as a separate class. In the dynamometer type of instrument the current in the moving element is produced by conduction through the hairsprings or the commutator, while in the induction-type instrument the current in the moving element is produced by electromagnetic induction (transformer action). It is therefore immediately evident that such an instrument can function only in alternating-current circuits. In a direct-current circuit there would be no flux changes and consequently no transformer action.

The moving element of the induction-type instrument usually consists of an aluminum disc or drum. Aluminum is used because of its lightness. This aluminum disc is placed in the magnetic field of one or more electromagnets. The magnetic circuit of this type of instrument is usually composed largely of laminated iron. In the magnetic circuit there are one or more air gaps and the aluminum disc or drum is arranged to rotate in the air gap. The placing of an aluminum disc in a pulsating magnetic field will, in itself, produce no torque; but, by using the so-called shading coil, it is possible to produce the necessary phase displacement between the two parts of the pole so that torque will be produced. The shading coil consists of a short-circuited copper ring placed around one half of the pole of the electromagnet. This short-circuited ring of copper opposes the increase in flux because of the counter magnetomotive force of the induced currents in the copper ring. It will also oppose the decrease in flux a half cycle later for the same reason. Therefore the flux in the half pole surrounded by the copper ring will lag in time phase behind the flux in the other half of the pole by an angle approaching ninety degrees. Flux relations similar to those in a two-phase induction motor are obtained. A restraining force consisting of two hairsprings is used for the indicating instruments, and a dissipative restraining force is used for the integrating instruments. A dissipative restraining force is usually obtained by allowing the same aluminum disc to rotate between the poles of one or more permanent magnets. Thus the driving torque is produced in one part of the disc and the opposing torque in another part of the same disc.

The induction-type instrument can be used as an ammeter. In this case the electromagnet is wound with a few turns of heavy wire. By carefully selecting the quality of iron in the magnetic circuit, the flux will be made nearly proportional to the current flowing in the electromagnet. The current induced in the aluminum disc is proportional to the rate of change of flux. Consequently the torque acting will be proportional to the square of the current flowing in the coil. Therefore, by using a spring whose countertorque is proportional to the deflection and by using a square-root scale, the meter can be made to read directly the effective value of the current. This type of ammeter has one serious disadvantage. Since the torque acting is proportional to the square of the current, this type of meter is very likely to be damaged by excessive current. When used in a power plant the momentary current through the instrument at times of system trouble may be many times normal, and the resulting torque in the instrument may be sufficient to damage it seriously.

The induction-type instrument can also be used as a voltmeter. If the electromagnet is placed in series with a high resistance the current flowing will be approximately proportional to the impressed difference of potential. In order to be accurate at different frequencies it is necessary that the series resistance be large compared to the inductive reactance of the electromagnet. Since the magnetic circuit is composed largely of iron, this is difficult to accomplish. Consequently this type of instrument is satisfactory only over a narrow range of frequencies.

The induction type of instrument may also be used as a wattmeter. In this case there are one or more current coils and one or more potential coils. These coils are so arranged that the currents produced in the aluminum disc by flux changes in one coil will flow under the influence of the magnetic field of one or more of the other coils. The potential circuit is made highly inductive so that the current will lag behind the impressed difference of potential by nearly ninety degrees. By placing a second winding of a few turns on the potential coil and short-circuiting this second coil through a variable resistance, it is possible to adjust the resistance so as to obtain exactly ninety degrees lag of the flux in the potential circuit behind the impressed difference of potential (see Fig. 15 on page 39).

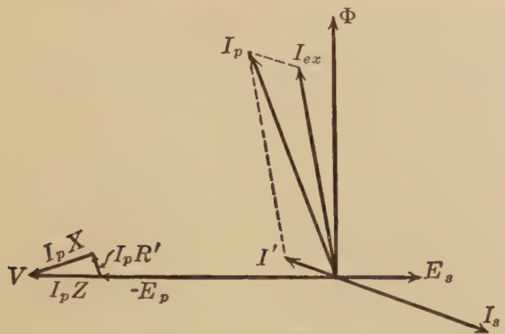

FIG. 15. Vector diagram for an induction wattmeter or watt-hour meter

V, impressed difference of potential; Φ, mutual flux; E_s, e. m. f. induced in short-circuited winding; $-E_p$, component of V which overcomes the e. m. f. induced in the potential coil; I_{ex}, exciting current in potential coil; I', current in potential coil due to current in short-circuited coil; I_s, current in short-circuited coil; I_p, total potential coil current; Z, R', X, impedance, resistance, and leakage reactance of potential coil, respectively. In the above vector diagram, I_s has been so adjusted that V is at right angles to Φ. This is the adjustment desired for proper operation of the meter

Again, this meter is similar to the two-phase induction motor, the flux of one phase being proportional to the load current and the flux of the other phase being proportional to the difference of potential. Therefore the torque acting will at each instant be proportional to the product of instantaneous current and instantaneous difference of potential. Since the moving element has considerable inertia the needle will assume a steady deflection proportional to the average power.

If the conservative restraining force is replaced by a dissipative restraining force the instrument becomes a watt-hour meter. This is accomplished by allowing the aluminum disc to rotate between the poles of permanent magnets. Thus the same aluminum disc acts both as the moving element and the dissipative restraining force. Since the torque is proportional to power, the number of revolutions will be proportional to the product of power and time. Therefore, the meter can be calibrated to read the energy which has been consumed. This is usually measured in kilowatt hours. A certain amount of friction is present in this meter but it is considerably less than in the dynamometer type of watt-hour meter due to the absence of brush friction. This meter is compensated for friction by placing an adjustable shading coil between the potential coil and the aluminum disc.

EXPERIMENT 2–E

The Study and Calibration of an Induction-Type Watt-Hour Meter

Object. To study the mechanical construction and arrangement of parts in an induction-type watt-hour meter. To calibrate the watt-hour meter by comparing its readings with those of a standard watt-hour meter.

Reference. National Electric Light Association, "Electrical Meterman's Handbook."

Apparatus. An induction-type watt-hour meter. A standard watt-hour meter. The necessary current-limiting rheostat for use as a load.

Method. Connect the current coils of the two watt-hour meters in series and their potential coils in parallel. By means of the switch in the potential circuit of the standard watt-hour meter start this meter when a definite point on the disc of the meter under test is in a given position. Allow the standard watt-hour meter to run while the meter under test makes a definite number of complete revolutions. Then stop the standard meter by means of the switch in its potential circuit. The number of revolutions made by the standard watt-hour meter multiplied by its disc constant should be equal to the number of revolutions made by the watt-hour meter under test multiplied by its disc constant. Any difference between these two products represents the error of the watt-hour meter being tested. Take readings as above for various loads ranging from light load to two hundred per cent of rated load. Now adjust the meter by moving the permanent magnets in or out as required, so that it will read correctly at rated load. Adjust the meter by moving the friction-compensating disc so that it will read correctly at 5 per cent of its rated load. After making the above adjustments, take another complete set of readings so that the correction curve can be plotted from zero to 200 per cent of rated full load.

Curves. Plot the correction curves as obtained before adjusting the meter and after adjusting the meter, using per cent of registration as ordinates and per cent of rated current as abscissas. Per cent of registration is the ratio of recorded watt hours to actual watt hours.

Questions. 1. Why is the light-load adjustment on this meter made at 5 per cent load while the light-load adjustment on the dynamometer type of watt-hour meter is made at 10 per cent load?

2. How is the light-load adjustment of this meter affected by changes in line voltage?

3. How is the accuracy of this type of meter affected by changes in temperature?

4. Should the potential circuit of the meter be connected to the line or the load side of the current coil? Why?

26. Soft-iron instruments. If in the dynamometer type of ammeter or voltmeter the moving coil be replaced by a piece of soft iron there results a new type of instrument known as the soft-iron or magnetic-vane type. In this type of instrument the piece of soft iron becomes magnetized by the field of the stationary coil. There results an interaction between the piece of soft iron and the magnetic field of the fixed coil which produces a certain torque. Since an increase in current will increase the magnetization of the piece of iron, as well as increase the field strength of the fixed coil, the torque produced becomes a function of the square of the current flowing. This, of course, holds only if there is no residual magnetism and if the magnetization of the iron is directly proportional to the field strength. These conditions can be approximated by using a suitable quality of iron. The ideal soft-iron instrument should operate with equal accuracy in either a continuous- or an alternating-current circuit. But since it is impossible to obtain a quality of iron having no residual magnetism and a straight-line B–H curve, the instrument can be calibrated to read correctly at only one frequency. However, its accuracy over a narrow range of frequencies is remarkably good.

When this type of instrument is used as a voltmeter it is necessary that the stationary coil be placed in series with a high limiting resistance. The reason for this has been explained in discussing the dynamometer type of instruments. Since the moving element consists only of a piece of soft iron it is unnecessary to use the springs as conductors. Thus the problem of a suitable conservative restraining force is somewhat simplified. This type of instrument is used neither with a dissipative

restraining force nor as a wattmeter. Instruments of this type are considerably cheaper than dynamometer instruments. They

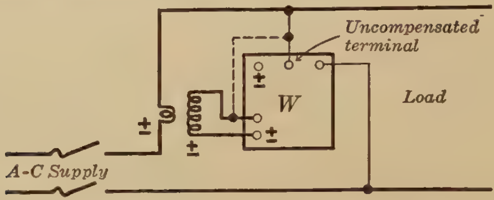

FIG. 16. A current transformer used in connection with a wattmeter

are very satisfactory for general switch-board and laboratory work where a high degree of accuracy is not necessary.

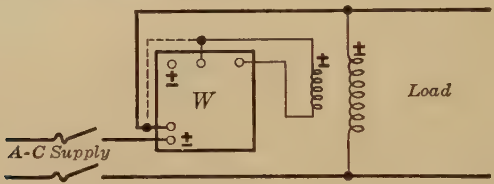

FIG. 17. Potential transformer used in connection with a wattmeter

27. The use of instrument transformers in single-phase measurements. For metering alternating-current circuits of high potential or high current it is usually preferable to use low-voltage or low-current instruments in connection with instrument

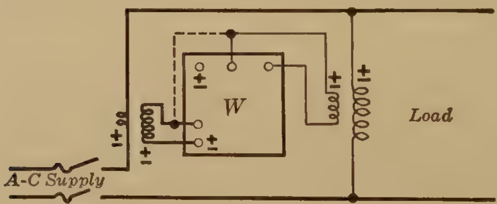

FIG. 18. Current and potential transformers used with a wattmeter

transformers to extend their range. (See Chap. VIII.) The use of instrument transformers in connection with voltmeters and ammeters extends their range by the transformer ratios. When an instrument transformer is used in connection with a wattmeter, certain precautions are necessary. In the simple wattmeter connection shown in Fig. 12, it will be noted that the

current taken by the potential coil also flows through the current coil and that the compensating coil prevents the meter from reading the loss in its own potential circuit. If a current

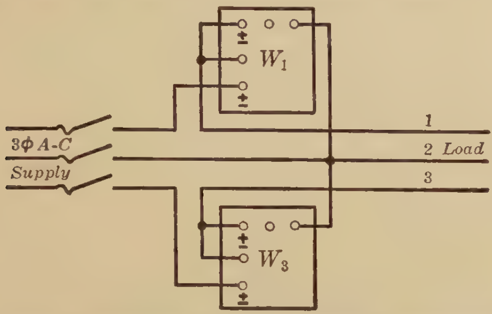

FIG. 19. The two-wattmeter method of measuring three-phase power

transformer is used in connection with a wattmeter as shown in Fig. 16, the current taken by the potential coil no longer flows through the current coil but through the primary of the current transformer. Only a small current, proportional to the primary current (depending on the ratio of the current transformer)

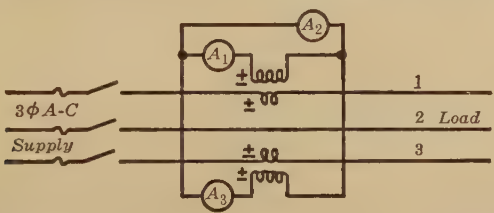

FIG. 20. The use of three ammeters and two current transformers for measuring three-phase currents

will flow in the current coil. Consequently the wattmeter should be uncompensated. To avoid any difference of potential between the movable coil and the current coil the connection shown by the dotted line in Fig. 16 should be made.

Fig. 17 shows the proper connections for the use of a potential transformer in connection with a wattmeter. Fig. 18 shows the proper connections for the use of both current and potential transformers in connection with a wattmeter. When dealing with high potentials, the connection shown by the dotted line in Fig. 18 should be grounded for the sake of safety.

28. The use of instrument transformers in three-phase measurements. Fig. 19 shows the usual arrangement of two wattmeters for measuring three-phase power.

When the current is larger than the current-carrying capacity of the wattmeters, it becomes necessary to use two current transformers. In such a case it is also desirable to place the ammeters in the secondary circuits of the current transformers. Since the current in any one wire of a three-phase line is equal to the vector sum of the currents in the other two wires it is

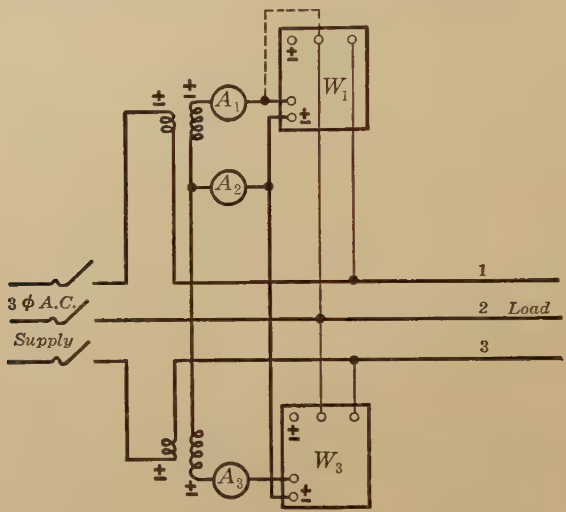

FIG. 21. The metering of three-phase current and power, using current transformers but without potential transformers

possible to use three low-range ammeters in the secondaries of two current transformers for measuring the currents in each of the three wires. Fig. 20 shows such an arrangement. Ammeter No. 2 reads the vector sum of the currents in ammeters No. 1 and No. 3, which is a measure of the current in line No. 2.

Unless the polarity markings on the current transformers are observed and the connections are made accordingly, the ammeter No. 2 may read the vector difference instead of the vector sum. This can easily be checked by opening the switch in line No. 2 while a three-phase load is attached. Opening this switch should reduce the reading of ammeter No. 2 to zero.

When this method of measuring current is combined with the two-wattmeter method of measuring power, certain difficulties are encountered. In order to fulfill all metering requirements when using two current transformers, three ammeters, and two wattmeters for measuring three-phase power, the connections should be made as shown in Fig. 21. The dotted connection between the potential coil and the current coil of wattmeter No. 1 should be made in order to avoid the possibility of any difference of potential existing between the potential coils and the current

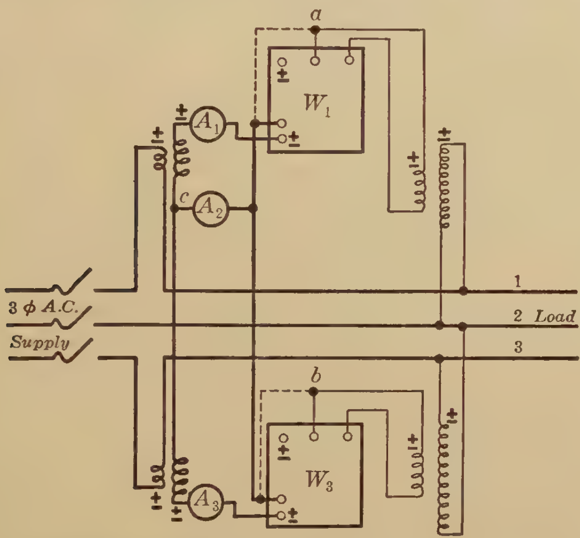

FIG. 22. Three-phase metering, using both current and potential transformers

coils of the wattmeters. The corresponding connection on wattmeter No. 3 is not necessary and should not be made since such a connection would constitute a shunt around ammeters No. 1 and No. 3.

When both current and potential transformers are used the connections become as shown in Fig. 22. The connections shown by dotted lines can be made in order to avoid electrostatic difficulties, but since this method of connection is usually used in connection with high-potential lines it is preferable to omit the connections shown by the dotted lines and instead to ground the points *a*, *b*, and *c*. When these points are grounded, the

number of connecting wires can be reduced as shown in Fig. 23. This method is the one usually used on switchboards in large power plants. By properly choosing the locations of the ground connections, a considerable saving in secondary wire can be made.

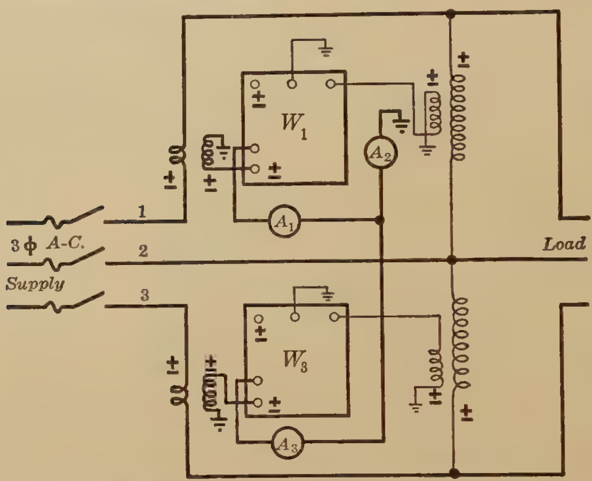

FIG. 23. Three-phase metering with the secondaries of current and potential transformers grounded

CHAPTER III

FLUX DISTRIBUTION

29. The magnetic circuit. An electric current possesses the property of producing and maintaining a magnetic field. This property is called its magnetomotive force.

The magnetomotive force M of a solenoid is equal to $\frac{4\pi NI}{10}$ gilberts, where

N = number of turns of wire, and
I = current in amperes.

The product NI is called ampere-turns.

The total number of lines of induction Φ that will be set up in the solenoid depends upon the magnetomotive force M and the reluctance $\mathcal{R}$ of the magnetic circuit.

$$\Phi = \frac{M}{\mathcal{R}}.$$

If the complete magnetic circuit is made up of one kind of material, and the cross section is uniform, the reluctance $\mathcal{R}$ is equal to $\frac{l}{\mu A}$, where

l = length of magnetic circuit in centimeters,
A = area of cross section of magnetic circuit in square centimeters,
μ = permeability of the material, and
$\mathcal{R}$ = reluctance of magnetic circuit in oersteds.

When the magnetic circuit is made up of two or more parts connected in series, the total reluctance is equal to the sum of the individual reluctances. When the magnetic circuit is made up of two or more parts connected in parallel, the total reluctance is equal to the reciprocal of the sum of the reciprocals of the individual reluctances.

The permeability of air is 1. The permeability of a given sample of iron depends upon the chemical composition and

physical structure of the material and upon the density of the lines of induction within it. If the flux density of iron is increased, the permeability increases until a certain range of flux density is reached. If the flux density is increased above that range, the permeability decreases quite rapidly.

The ballistic galvanometer is commonly used for measuring magnetic flux. To make these measurements the ballistic galvanometer is connected to a secondary coil which encircles the magnetic circuit. If the flux in the magnetic circuit remains constant, the galvanometer indicates zero. If the flux is suddenly changed, the galvanometer coil begins to move. The final deflection multiplied by a constant is a measure of the change of flux. This method of measuring flux has three disadvantages. First, it is necessary to change the flux in order to measure it; second, the change of flux must be rapid, in order that the electric discharge may be completed before the galvanometer coil moves appreciably; and third, the indications are instantaneous, as the moving coil immediately returns toward zero.

The above disadvantages can be overcome by using the Grassot fluxmeter. This meter is essentially a ballistic galvanometer except that the moving coil is suspended by a single cocoon fiber of negligible torsional stiffness, and therefore the coil remains practically at rest in any position. A small exploring coil may be connected to the terminals of the fluxmeter. If the exploring coil is placed in a magnetic field so that the lines of induction pass through it, the fluxmeter starts into motion and comes to rest in a new position, the deflection being directly proportional to the flux within the coil. When the exploring coil is moved, the needle of the instrument follows the variation of the flux within the coil. If the exploring coil is removed from the magnetic field, the fluxmeter needle returns to zero. The fluxmeter may be calibrated to read directly in maxwells.

30. Flux distribution throughout the air gap of a generator or motor. The flux distribution throughout the air gap of a generator or motor can be determined in the following simple manner. A coil consisting of a few turns of fine wire is wound on the armature so as to embrace 180 electrical degrees of the periphery. A ballistic galvanometer (or millivoltmeter) is attached to the ends of this coil. If the field is excited and the

field current suddenly interrupted or reduced, the maximum deflection of the instrument will be proportional to the change in the number of lines of induction enclosed by the coil. If the coil is revolved into different angular positions in regard to the poles, and the field current is varied (and the flux consequently changed) over the same range each time, a series of galvanometer readings can be obtained which will be proportional to the changes of flux enclosed by the coil in its various positions. The change of flux enclosed by the coil is proportional to the total flux enclosed by the coil in its various positions when the field current is varied from a given maximum value to a given minimum value each time.

These readings of total flux enclosed by the coil do not give the flux density at any point, but if two successive readings with only small angular displacement between them are taken, then the difference in the flux enclosed in the two positions gives the change of flux density in that portion of the air gap occupied by the conductors of the coil. This is assuming that the change is the same for both sides of the coil, which is practically true since they are 180 electrical degrees apart and in the same relative position to a north and south pole, respectively. Then if a curve is plotted, using galvanometer deflections as ordinates and angular displacements as abscissas, the result shows the flux enclosed by the coil throughout the field. The first derivative of this will be a curve showing the change of the flux enclosed by the coil or the change of flux density in the positions occupied by the coil conductors. The latter curve shows the distribution of the flux throughout the air gap and is the one desired. If the curve of flux enclosed by the coil is plotted for angular positions occupied by the center of the coil, then the first-derivative curve must be displaced 90 degrees along the horizontal axis. This will be a true flux distribution curve, since it represents the change of flux at the conductors which are 90 degrees from the center of the coil.

The flux distribution throughout the air gap of a generator or motor can be determined by the use of the Grassot fluxmeter. Since the exploring coil has of necessity a considerable area, the meter reading does not represent the flux density at any one point, but does represent the average flux density within the area enclosed by the coil.

EXPERIMENT 3-A

Determination of No-Load Flux Distribution throughout the Air Gap of a Generator or Motor; Ballistic Method

Object. To determine the no-load distribution of flux throughout the air gap of a generator or motor.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XV.

Apparatus. A dynamo. A ballistic galvanometer or millivoltmeter. An ammeter. A length of fine wire. Switches and rheostats for controlling the field current.

Method. On the periphery of the armature, wind a coil consisting of a few turns so as to embrace 180 electrical degrees. Attach the ends of the coil to the ballistic galvanometer or millivoltmeter. Connect the field of the dynamo to a suitable source of power, and place in series with the field a resistor that is shunted with a snap switch which can be opened with a uniform motion each time. An ammeter and rheostat should be connected in series with the field so that the current can be brought to the same value each time before the switch is opened. For different positions of the coil, close the switch which shunts the resistor and leave it closed for a few seconds; adjust the current to the proper value, then open the switch quickly and note the maximum deflection of the ballistic galvanometer or millivoltmeter.

Plot a curve, using galvanometer deflections as ordinates and angular displacements as abscissas. Plot a curve which is the first derivative of the above curve.

Question. Why should the coil span 180 electrical degrees on the armature periphery?

EXPERIMENT 3-B

Determination of Flux Distribution in the Air Gap of a Generator or Motor; Double-Pilot-Brush Method

Object. To determine the no-load and full-load flux distributions in the air gap of a dynamo by the double-pilot-brush method.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XV.

Apparatus. A dynamo. A low-range voltmeter. A template made of cardboard or tough paper with holes or saw teeth for pencil points. The necessary meters and equipment for loading the dynamo as a generator or motor.

Method. Arrange a cardboard or tough-paper template with holes or saw teeth for pencil points. The holes or teeth should be uniformly spaced so that the distance between them corresponds to a definite number of commutator bars (usually one bar). The paper template is greased, placed on the commutator, and securely fastened to the machine so that it will not move as the armature rotates. The voltmeter leads should be connected electrically to the leads of hard drawing pencils. The difference of potential on the commutator between adjacent template holes or teeth is read on a low-range voltmeter by inserting the pencil points in the adjacent holes or vees.

By gradually moving the pencil points along the paper template, when the machine is running at no-load with the proper field excitation, the flux distribution is determined over the whole pole pitch. The experiment is then repeated with the machine loaded. This gives different results because the flux is redistributed due to armature reaction. The observed voltmeter readings must be corrected in this case for the IR drop in the armature coils between pencil points. If the dynamo is being tested as a generator, the correction is added. If the dynamo is being tested as a motor, the correction is subtracted.

Precautions. Do not use metal points, as they may scratch the commutator. Fasten the template securely so that it will not slip during the test.

Curves. Plot a no-load flux-distribution curve, using electromotive forces as ordinates and angular positions of the pencil points as abscissas. Plot a full-load flux-distribution curve.

Question. Why do electromotive forces plotted against angular positions give a flux-distribution curve?

31. The leakage coefficient. The purpose of the field magnet of a dynamo is to send magnetic flux through the armature, that is, through the part of the armature which carries the active portion of the conductors. But, because of the surrounding air which forms a path parallel to the path of flux through the

armature, a portion of the total flux does not enter the armature. The ratio between the total and the useful flux is called the leakage coefficient. The ratio is always greater than one.

The leakage coefficient of a dynamo can be measured in the following manner. A coil made up of three or four turns of fine wire is placed on the field spool, and a coil with a like number of turns of wire is placed on the armature so that 180 electrical degrees of the armature are spanned. Electrical connections are made so that the field current can be changed quickly. A ballistic galvanometer is first connected to one coil, and the maximum deflection is noted when the field current is rapidly changed by a definite amount. Then the galvanometer is connected to the other coil, and the deflection is noted when the field current is changed in exactly the same manner as before. The ratio of the galvanometer reading, when the galvanometer is connected to the coil around the field spool, to the galvanometer reading when the galvanometer is connected to the coil on the armature periphery is the leakage coefficient.

EXPERIMENT 3-C

The Leakage Coefficient of a Generator or Motor

Object. To determine the leakage coefficient of a generator or motor and to study the relation between the coefficient and the flux density at different field strengths.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. I, Exp. 26.

Apparatus. A generator or motor. A ballistic galvanometer or millivoltmeter. An ammeter. Two lengths of fine wire.

Method. Place a coil consisting of three or four turns of fine wire around one field spool. Place a coil consisting of a like number of turns on the periphery of the armature so that it will carry the useful flux of the above field pole. Place the ammeter in the field circuit and arrange a snap switch in parallel with a resistor so that the field current can be changed quickly. Then connect the ballistic galvanometer to one of the coils and note the maximum deflection when the field current is changed quickly. Connect the galvanometer to the other coil and note the maximum deflection when the field current is changed exactly as it was changed before. (It is preferable to take the

readings when opening the switch rather than when closing the switch.) Repeat the above test for different values of field current.

Plot the curve showing the change of leakage coefficient as the field current changes, using leakage coefficients as ordinates and field currents as abscissas.

Questions. 1. If the coefficient is constant over the range of field current used, what do the results indicate?

2. How do the results compare with published data on coefficients for the type of machine tested?

3. Of what use is the leakage coefficient?

CHAPTER IV

DIRECT-CURRENT MOTORS

32. Fundamental principles. A dynamo-electric machine is a machine for transforming mechanical energy into electrical energy, or vice versa. If the dynamo receives electrical energy from some outside source and converts the electrical energy into mechanical energy, it is called a motor. If the dynamo receives mechanical energy from some outside source and converts the mechanical energy into electrical energy, it is called a generator. Structurally, the direct-current motor is exactly like the direct-current generator, and consists of an electromagnet, an armature, and a commutator with its brushes.

If a current-bearing conductor is placed at right angles to a magnetic field, the conductor will tend to move at right angles to the field and the conductor. The direction of the tendency for motion may be determined by Fleming's left-hand rule. The rule may be stated as follows: Extend the thumb, forefinger, and center finger of the left hand so as to form right angles with each other. If the forefinger points in the direction of the magnetic flux and the center finger points in the direction of the current in the conductor, the thumb will indicate the direction in which the conductor tends to move.

The conductor will be acted upon by a force

$$F = Bl\bar{I} \text{ dynes,}$$

where B = number of lines of induction per square centimeter,
l = length in centimeters of conductor immersed in the magnetic field,
and $\bar{I}$ = current flowing in abamperes.

The motion of an ordinary direct-current motor is due to the reaction between current flowing in a set of conductors on the armature, and a magnetic field produced by electromagnets, in which the current-bearing conductors are immersed.

The purpose of the commutator on the ordinary direct-current motor is to allow the electric current to flow through the conductors in the proper direction at the proper time, in order that the tendency for armature rotation will be in the same direction all the time.

Most armatures are of the drum type. In this form the core is made with slots in which the wires lie. The conductors may be connected one to another to form either a lap winding or a wave winding. (See § 44.)

The armature core is made of iron and serves a double purpose. It is a mechanical structure for mounting the conductors, and thus it serves as a medium for transferring the forces produced in the conductors to the shaft. The second purpose of the iron in the armature core is to lower the reluctance of the magnetic circuit, and thereby lessen the ampere-turns required on the field structure to set up the required flux. The armature iron core is laminated to cut down eddy currents and the corresponding energy loss.

The field windings may be connected in four different ways:

First. The terminals of the field winding may be connected to some external supply of electric current other than the source of current supply to the armature. This is known as separate excitation for the motor.

Second. The field winding may be connected across the armature terminals; the armature is then connected across the supply difference of potential. A motor with field windings connected in this way is a shunt motor.

Third. The field winding may be connected in series with the armature so that the armature current flows through the field winding. A motor with its field windings connected in this way is called a series motor.

Fourth. Two field windings may be used. One is connected in series with the armature, and the other is connected across the armature terminals or across the supply lines. This motor is known as a compound motor.

- *a.* The motor is cumulatively compound if the two windings are so connected that their magnetomotive forces are additive.
- *b.* The motor is differentially compound if the two windings are so connected that their magnetomotive forces are opposing each other.

EXPERIMENT 4–A

A Study of Direct-Current Dynamos

Object. To study the structural and electrical details of several dynamos.

Reference. Christie, "Electrical Engineering," Chap. VII.

Apparatus. In the study of the dynamo one or more machines can be used for detailed examination. Other types can be used for more general study.

Theory. Dynamos are divided into classes according to their use as generators or motors, the service they are to render, their mechanical construction, and the manner of electrical connections.

direct current

1. *Types.* Dynamos may be constant-voltage or constant-current generators, constant-speed, variable-speed or adjustable-speed motors, horizontal-shaft or vertical-shaft, open, semi-enclosed, or closed, etc.
2. *Field magnets.* Field magnets may be bipolar or multipolar. There is a so-called unipolar, or homopolar, type of dynamo, which is seldom met in practice.
3. *Field excitation.* The field winding of the dynamo may be connected shunt, series, or compound.
4. *Field poles.* Field-magnet cores may be solid or laminated. Sometimes separate pole shoes are used. Sometimes the ends of the cores, widened more or less, serve as pole pieces.
5. *Field coils.* Field coils may be wound on bobbins or may be form-wound. In the latter case the coils are held together by tape.
6. *Armature.* The most important type of armature is the drum armature.
7. *Armature core.* The armature stampings may be assembled directly on the shaft or on a spider which is keyed to the shaft.
8. *Armature winding.* The winding may be arranged as a lap winding or as a wave winding. It may be simplex, duplex, triplex, etc. It may be singly reëntrant, doubly reëntrant, triply reëntrant, etc.
9. *Armature leads.* The armature leads may be connected directly to the commutator bars or to risers connected thereto.
10. *Bearings.* The two common types of bearings are the ring-oiled bearing and the ball bearing.

Method. Make a report on one or more assigned motors or generators, as follows:

1. Type of machine.
2. Rating of machine.
3. Field magnets.
4. Field excitation.
5. Field coils.
6. Field poles.
7. Armature core.
8. Type of armature winding.
9. Number and dimensions of commutator bars.
10. Type of bearings and dimensions of same, with sketch.
11. Make a sketch showing a transverse section of the machine and give the lengths of the mean flux path in each part of the magnetic circuit.
12. Peripheral speed of armature and of commutator.
13. Connection of armature leads.
14. Number of brush sets and number of brushes per set.
15. Current density at brush contacts.
16. Sketch the outline of the machine, showing the location of the various terminals.
17. Make a sketch of the proper electrical connections, naming the various parts.
18. Discuss tests for determining the type of winding (simplex, duplex, triplex, etc.).
19. Measure depth of air gap and dimensions of slots.
20. From field-spool dimensions and resistance measurements calculate the number of field turns.

Questions. 1. What other types of armatures are sometimes used?

2. What are the advantages of the drum-type armature?

33. Starting boxes. When a motor is connected across the line, some special means must be provided for avoiding too great a current in the armature at the start. The counter electromotive force of a motor is zero when the motor is standing still, and therefore at the instant of connecting the motor to the line the armature current is limited only by the resistance of the armature circuit, which is relatively small.

It is necessary, therefore, to insert a certain amount of resistance in series with the armature when the motor is to be

started, so that the armature current will be limited to a reasonable value when the motor is connected to the line. As soon as the armature begins to rotate, an electromotive force is set up which is in opposition to the impressed difference of potential, and the armature speed soon becomes sufficiently high to produce a counter electromotive force large enough to limit the armature current to a reasonable value. As the motor increases in speed, the resistance inserted into the armature circuit may be gradually reduced and finally removed entirely.

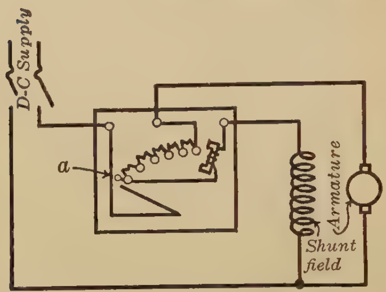

FIG. 24. Starting box, manufactured by the Cutler-Hammer Manufacturing Company, connected to a shunt motor

A piece of equipment designed especially for the purpose of limiting the current through the armature during the starting period is known as a starting box, or starting rheostat. Figs. 24 and 25 illustrate the wiring of two starting boxes. Fig. 24 is the wiring diagram for a starting box made by the Cutler-Hammer Manufacturing Company. Fig. 25 represents the wiring diagram of a General Electric Company starting box. The starting box shown in Fig. 24 is equipped with a weak-field release. The starting box shown in Fig. 25 is equipped with an under-voltage release.

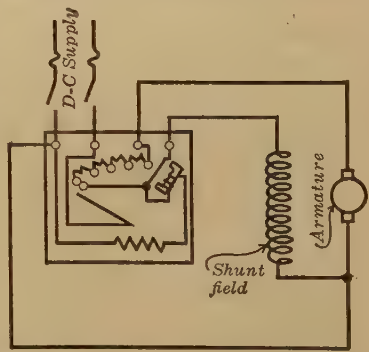

FIG. 25. Starting box, manufactured by the General Electric Company, connected to a shunt motor

A spring will pull the arm back to the starting position for both starting boxes when the current in the holding coil is reduced to a certain value.

To start the motor, the supply switch is closed and the arm on the starting box is moved clockwise until the first contact is made. The current then passing through the armature circuit is limited by the resistance shown, plus the resistance of the

armature. As the motor speeds up the arm is moved farther to the right, and when the motor is practically up to full speed, the arm should be on the last notch so that the armature is directly across the line.

In the three-point box the field current energizes the small holding magnet shown in Fig. 24. This will hold the arm in place. If the field current should become low for any reason, the arm will return to the extreme counterclockwise position and stop the motor. The resistance of the holding coil is very small when compared with the resistance of the shunt field.

The operation of the four-point box (Fig. 25) is different in some respects from that of the three-point box. The holding coil does not carry the field current in the four-point box. Therefore a large decrease in field current, with the impressed difference of potential kept constant, will not cause the arm to be released. The holding coil is connected in series with a current-limiting resistance, and when the arm is placed on the first notch, the coil is excited directly from the line.

34. Resistance units for starting boxes. The number of resistance steps and the size of the steps to be placed in a starting box for a shunt motor may be determined readily. Let us assume that a starting current of 120 per cent of full-load rating is satisfactory. A starting box should be designed to start a motor under full-load torque.

Let I_a = full-load armature current,
r_a = armature resistance,
R_1 = total resistance in starting box to be connected in series with armature (corresponding to arm on first notch),
R_2 = resistance placed in series with armature when arm is on second notch,
R_3 = resistance placed in series with armature when arm is on third notch,
E = induced electromotive force in motor,
and V = line difference of potential.

Let us assume that R_1 is so adjusted that the current at the instant of throwing the arm on the first notch is $1.2\ I_a$.

$$1.2\ I_a = \frac{V}{r_a + R_1} \quad \text{and} \quad R_1 = \frac{V - 1.2\ I_a r_a}{1.2\ I_a}.$$

The armature current will drop to I_a in a short time. Then

$$I_a = \frac{V - E_1}{r_a + R_1},$$

where E_1 is the induced electromotive force in the motor at this time.

If R_1 in the above equation is replaced by its determined value, it can be readily shown that $E_1 = \frac{V}{6}$.

When the arm is moved to the second notch, the armature current should reach $1.2\ I_a$. Therefore, at the instant of moving the arm to the second notch, the relation

$$1.2\ I_a = \frac{V - \frac{V}{6}}{r_a + R_2}$$

must hold, so that $R_2 = \frac{\frac{5}{6}V - 1.2\ I_a r_a}{1.2\ I_a}$.

The armature current will reach I_a in a short time.

$$I_a = \frac{V - E_2}{R_2 + r_a},$$

where E_2 is the new value of induced electromotive force in the motor.

If R_2 in the above equation is replaced by its determined value shown above, it can be readily shown that $E_2 = \frac{11}{36}V$.

Resistance R_3 must be adjusted so that the armature current will reach $1.2\ I_a$ again when the arm is moved to the third notch. Then

$$1.2\ I_a = \frac{V - \frac{11}{36}V}{r_a + R_3},$$

and R_3 can be readily determined.

This process should be continued until all the unknowns are determined.

The speed of the motor will be proportional to E, so that the speeds of the motor for different positions of the starting-box arm can be estimated.

EXPERIMENT 4–B

A Study of Starting Boxes

Object. To study the construction of the various types of starting boxes that are used for starting shunt motors.

Reference. Ricker and Tucker, "Electrical Engineering Laboratory Experiments," Exp. 17. McGraw-Hill Book Company, Inc.

Apparatus. Different types of starting boxes for examination and study. At least one of the three-point type and one of the four-point type.

Method. Open up the starting boxes so that the internal circuits can be traced. Make complete wiring diagrams of the internal connections. Measure the resistance of each step of one of the starting boxes. Measure the resistance of the holding magnet.

Precautions. Do not overheat the starting box while measuring the resistance.

Questions. 1. What are the relative advantages of the three-point and of the four-point types of starting boxes?

2. Why is it necessary to use starting boxes with all large shunt, series, and compound motors?

3. Are starting boxes necessary with small motors?

4. What is the purpose of the contact button marked *a* in Fig. 24?

35. Selection of starting box. The selection of a starting box for a particular motor is very important. The name-plate rating of a starting box gives the rating of the motor for which it is designed. The difference of potential and horse-power ratings stamped on the name plate of the starting box should agree with the corresponding motor ratings.

If a 110-volt, 10-horse-power box is used to start a 220-volt, 10-horse-power motor with a 220-volt supply, the armature current will be approximately four times normal at the start, and the heating in the armature during that period will be about sixteen times normal.

36. Field rheostats. It is frequently necessary to regulate the shunt-field current of generators and motors. This is usu-

ally accomplished by placing a variable resistance in series with the shunt field. When this variable resistance is especially designed for use in the shunt-field circuit of a dynamo, it is called a field rheostat. The name plate on a field rheostat gives the following items: voltage, two current ratings, resistance in ohms or minimum field ohms.

A field rheostat is usually designed for use with one particular dynamo, and the voltage rating on the rheostat corresponds to that of the dynamo. The current ratings are of greater importance since field rheostats are often damaged by being overheated from excessive current. When only a small part of the rheostat's resistance is being used, the heat generated in that sector is carried away by conduction to the adjacent cool parts, as well as being dissipated directly to the atmosphere. The larger current rating stamped on a field rheostat is the maximum current which it can carry continuously without overheating when only a small portion of the total resistance is being used. When all the resistance is being used, there are no cool portions and all the heat generated must be dissipated directly to the atmosphere. The smaller current rating stamped on a field rheostat is the maximum current which it can carry continuously without overheating when all the resistance is being used.

The resistance rating represents the maximum resistance of the field rheostat. On some makes of rheostats "minimum field ohms" appears on the name plate. This signifies that if the shunt-field resistance is at least equal to that stamped on the rheostat, and if the voltage rating of the rheostat is the same as that of the dynamo with which it is to be used, then the current will at no time be greater than the safe carrying capacity of the rheostat.

37. Reversing the direction of rotation of a motor. A study of Fleming's left-hand rule (§ 32) brings out the fact that the direction of rotation of a motor will reverse if the direction of the current through the armature conductors is changed or if the direction of the lines of induction in the field poles is reversed. Changing the direction of both armature current and field flux will not reverse rotation.

Therefore, if the direction of rotation for a motor is to be changed, the field terminals should be reversed, so that the field current will flow in the opposite direction, or the current through the armature must be reversed.

EXPERIMENT 4-C

The Starting and Operating of Shunt Motors

Object. To learn the necessary procedure and precautions for starting, operating, and reversing the direction of rotation of a direct-current shunt motor.

Reference. James, "Controllers for Electric Motors," Chap. I. D. Van Nostrand Company.

Apparatus. A direct-current shunt motor and a starting box of corresponding rating, preferably a starting box used in Experiment 4-B. Some means of loading the motor, preferably a Prony brake.

Method. Connect the assigned motor and starting box to a suitable source of power. Practice starting the motor several times. Reverse the field terminals and note the result. Reverse the armature terminals and note the result. Reverse the line terminals and note the result.

Connect an ammeter of suitable range in series with the armature. Note the first rush of current as the starting arm is moved to the first contact. Note the steady value of current with the arm on the first contact. Note the current as the arm is moved to each successive point. Load the motor so that it will develop about full-load torque and repeat the above. With the motor loaded move the starting arm two points at a time and note the results. Measure the resistance of the armature and starting box.

Precautions. In checking the wiring of a shunt motor always trace the path of current from one line through the starting box, through the armature, and to the other line. Also trace a circuit from the first line through the starting box, through the shunt field, and to the other line. One field terminal and one armature terminal will then be connected directly to one side of the line. Do not move the starting arm past the first notch until the motor has started to rotate. The handle of the box must never be moved too rapidly; to do so defeats the purpose of the starting box. The motor must not be allowed to run for any length of time with the starting resistance wholly or partly in the circuit; to do so is likely to overheat the starting box. In starting a motor never allow the arm to move backwards as the resulting arc may damage the contacts and may also burn the fingers.

Keep one hand on the main switch during the starting period, and if, for any reason, it becomes necessary to stop the motor, open the main switch before allowing the starting arm to move backwards.

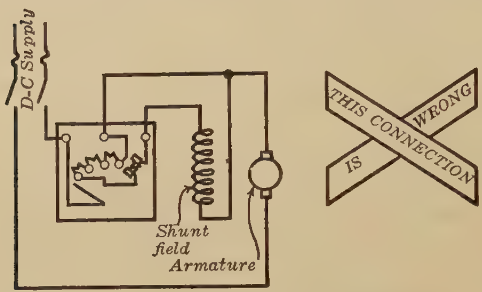

FIG. 26. A wrong connection for a starting box and shunt motor

Questions. 1. What determines the current that the motor takes on the first notch?

2. Assuming that the motor draws 15 amperes after steady conditions have been reached with the arm on the third notch, what will the first rush of current be as the arm touches the fourth notch?

3. Assuming the motor and starting box used in this experiment, draw a curve showing how the current in the armature circuit varies with respect to speed, as the speed of the motor increases with the starting arm on the first notch. In order to do this, it will be necessary to take a reading of current when the motor has reached its highest speed with the starting arm on the first notch.

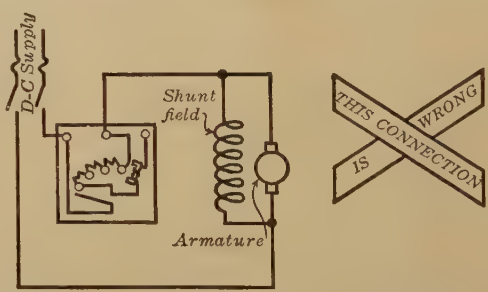

FIG. 27. A wrong connection for a starting box and shunt motor

4. How would the curve look if the contact had been made with the second notch of the starting box instead of having been made with the first?

5. What would be the effect on starting and operating if the motor were connected as shown in Fig. 26?

6. What would be the effect if connected as shown in Fig. 27?

In answering questions 5 and 6, the student should give a complete discussion of circuit conditions.

38. Static torque. After the shunt motor has been started,

$$i_a = \frac{V - E}{r_a}$$

and
$$V = i_a r_a + E, \tag{1}$$

where i_a equals armature current. Multiplying both sides of equation (1) by i_a gives the new equation

$$Vi_a = i_a^2 r_a + Ei_a.$$

The term $i_a^2 r_a$ represents the copper loss in the armature. The term Vi_a represents the power supplied to the armature. Therefore $Vi_a - i_a^2 r_a$ represents the total mechanical power developed in the armature, and this equals Ei_a watts.

If the total torque developed in the armature in pound-feet is represented by the letter T, then

$$Ei_a = \frac{2\,\pi TN}{33{,}000} \times 746 \text{ watts},$$

where
$$N = \text{revolutions per minute.}$$

Proof. Consider an armature of radius A feet. Assume it is rotating N revolutions per minute, and that the total force exerted on the periphery of the armature is G pounds. Then the foot-pounds of work performed per revolution of the armature equal $2\,\pi GA$. The work performed per minute equals $2\,\pi GAN$ foot-pounds. A horse power is a unit of power equal to a rate of 33,000 foot-pounds of work per minute. One horse power equals 746 watts.

Therefore, under the above conditions, the power expended in watts equals

$$\frac{2\,\pi GAN}{33{,}000} \times 746, \quad \text{or} \quad \frac{2\,\pi TN \times 746}{33{,}000}.$$

$$E \text{ for the motor} = \frac{p\Phi ZN}{a \times 60 \times 10^8} \text{ volts},$$

where
p = number of poles on motor,
Φ = flux per pole,
Z = number of armature conductors,
N = revolutions per minute of armature,
and a = number of armature paths.

Therefore,
$$\frac{p\Phi ZN}{a \times 60 \times 10^8} \times i_a = \frac{2\,\pi TN \times 746}{33{,}000},$$

or $$T = \frac{33{,}000}{746 \times 2\,\pi} \times \frac{pZ}{a \times 60 \times 10^8} \times \Phi i_a \text{ lb.-ft.},$$

or $$T = 7.05\,Z'\Phi i_a \text{ lb.-ft.},$$

where $$Z' = \frac{pZ}{a \times 60 \times 10^8}.$$

The above equation gives the general expression for the total torque developed in the motor armature.

If Φ is kept constant the relation between T and i_a is a straight-line law. When the static torque test is made for a shunt motor, the field current is held constant, but the flux per pole changes slightly with armature current due to armature reaction.

The relation between T and i_a for a series motor varies for different values of i_a. The flux Φ is almost proportional to i_a for low values of i_a, and T is therefore almost proportional to i_a^2. The iron becomes saturated for large values of i_a, so that T approaches a straight line as i_a is increased.

EXPERIMENT 4-D

The Static Torque of a Shunt Motor

Object. To determine the static torque of a direct-current shunt motor for different armature currents and different field excitations.

Reference. Langsdorf, "Principles of Direct-Current Machines," Chap. VII. McGraw-Hill Book Company, Inc.

Apparatus. A direct-current shunt motor equipped with a Prony brake. Rheostats for controlling the field and armature currents. A scale for weighing the force of the brake arm.

Method. Arrange the brake and scale so as to weigh the turning effort of the armature. Connect the armature, in series with a current-limiting rheostat, to a suitable source of power. Connect the shunt field, in series with its rheostat, to a source of potential at least 25 per cent greater than the rating of the machine. A considerable saving in power can be effected by using a source of comparatively low potential for supplying the armature circuit. This will reduce the amount of power which must be absorbed in the current-regulating rheostat.

Holding the field current constant, vary the armature current from a small value up to 50 per cent above the rated full-load

current. Take readings of the field current, the armature current, and the weight on the scale. Then hold the armature current constant at full-load value, and vary the shunt field current from zero to 25 per cent above normal. Take the same readings as above. Determine the effective weight of the brake. (See § 39.) Measure the resistances of the armature, and interpoles if present. Plot the necessary curves to illustrate your results.

Questions. 1. What factors determine the torque of a motor?

2. Why is the torque not proportional to the field current, for constant armature current?

3. Why does the static torque differ from the running torque for equal armature currents and the same field flux?

4. Calculate, for the condition of normal field excitation and full-load armature current, what the output of the machine would be at rated speed. Assume that 4 per cent of the static torque is necessary to overcome friction, windage, and iron losses.

5. Calculate the difference of potential necessary to impress upon the machine under conditions as given in question 4.

39. Brake tests. A common way of loading a small motor in order to study its operating characteristics is by use of the Prony brake. This method usually consists of a rope or clamp which grips a water-cooled pulley wheel that is located on the shaft of the motor. Any desired amount of power may be absorbed by adjusting the grip of the clamp upon the pulley. If a clamp is used, it is directly connected to a brake beam, and the beam is usually supported at the far end by a stand which rests on an ordinary scale platform, so that the force exerted at the end of the beam can be measured. The lever arm must be horizontal and the scale platform level.

The horse power delivered by the motor can be readily calculated, if the motor speed, length of brake arm, and the force exerted on the scale by the brake arm are known. The horse power delivered by the motor will equal

$$\frac{2\,\pi GAN}{33{,}000},$$

where G = the net weight in pounds on the scale = gross weight on scale minus the tare,

A = effective length of brake arm in feet, and

N = R.P.M.

When a rope brake is used, the length of the lever arm A is taken as the radius of the pulley plus the radius of the rope when taut. When a clamp-style Prony brake is used, the length of the lever arm A is taken as the distance from the center of the shaft to the point of contact between the lever arm and the stand which is located on the platform scale.

The tare can be determined by running the motor in one direction and taking the scale reading, then running the motor in the opposite direction, and taking the scale reading again. (It is assumed that the Prony brake is loosely adjusted but ready for operation.) The average of the two scale readings will be the tare, or the effective weight of the brake.

The efficiency of a motor for different loads can be readily determined if the proper instruments are used to measure the electrical input to the motor and the Prony brake is used for loading the motor and determining the output. The input and output must be expressed in the same power units. Then the efficiency $\eta = \dfrac{\text{output}}{\text{input}}$.

The regulation of a constant-speed direct-current motor is the ratio of the difference between the no-load and the rated full-load speeds to the rated full-load speed. It is assumed that the rated difference of potential is maintained constant and that the machine is at the normal operating temperature. The percentage regulation may be defined as the above ratio multiplied by 100.

The above method for loading small motors is very convenient. The scheme is not used for testing large motors, due to the high cost of building a Prony brake capable of absorbing the power output of the motor and the large amount of energy that would be wasted in making the test. Simple and less troublesome means have been devised for testing large motors. (See § 57.)

EXPERIMENT 4-E

Brake Test of a Shunt Motor

Object. To obtain the operating characteristics of a direct-current shunt motor operating from constant-potential mains.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. I, Exps. 66 and 67.

Apparatus. A direct-current shunt motor with suitable starting box and field rheostat. A Prony brake and scale or other satisfactory method of loading the motor and measuring its power output.

Method. Connect the motor to a suitable source of constant potential. Adjust the brake and scale for measuring the power output of the motor. Determine the effective weight and the length of the brake arm. Adjust for normal field current, and maintaining it constant, take readings of terminal potential, armature current, field current, speed, and the weight on the scale for different loads from zero to 150 per cent of rated full load. Take readings for both increasing and decreasing loads. Plot the following curves, using horse-power output as abscissas: armature current, power input, torque, efficiency, and speed.

Questions. 1. What is the percentage speed regulation of the motor?

2. How does armature reaction affect speed regulation?

3. What effect would a rise in temperature have upon regulation?

4. Upon efficiency?

EXPERIMENT 4-F

Brake Test of a Series Motor

Object. To obtain the operating characteristics of a direct-current series motor.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. I, Exps. 66 and 67.

Apparatus. A direct-current series motor and suitable starting equipment. A Prony brake and scale or other suitable means of loading and measuring the power output of the motor.

Method. Connect the motor to a suitable source of constant-potential supply. Take readings of terminal difference of potential, current, speed, and the weight on the scale, starting with a safe overload and reducing the load in steps until the maximum safe speed has been reached.

Shunt the series field with a resistance about four times as large as the resistance of the series field itself and take another set of readings similar to the first.

For each of the two sets of readings, plot the following curves, using horse-power output as abscissas: current, power input, speed, torque, and efficiency.

Precautions. When the load on a series motor is reduced, the field is also weakened. This causes the speed to increase. If the reduction of the load is carried far enough, the speed will go so high as to wreck the machine. If a rope brake is used, the rope may break or slip off the pulley. This would suddenly remove all the load and the speed would become excessive in a very short time. Positive measures must be taken to prevent this dangerous condition.

One simple and effective safeguard against excessive speed is a weak shunt field winding in addition to the series field winding. The ampere-turns of this shunt winding should be so adjusted as to produce just sufficient flux to limit the no-load speed to a safe maximum. With this arrangement, one must be absolutely certain that the two fields are cumulative in their action. The addition of this weak shunt field does not materially alter the series characteristics of the motor.

Questions. 1. How does shunting the series field affect the operating characteristics of the motor?

2. Why do the series motors on street cars not attain excessive speeds?

EXPERIMENT 4–G

Brake Test of a Compound Motor

Object. To obtain the operating characteristics of a direct-current compound-wound motor.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. I, Exps. 66 and 67.

Apparatus. A compound-wound motor with suitable starting box and field rheostat. A Prony brake and scale or other means of loading and measuring the power output of the motor.

Method. Connect the machine as a cumulative-compound motor. Perform the test in the same manner as explained in Experiment 4-E. Reverse the series field so that the motor will be connected as a differential-compound motor and repeat the test.

Precautions. Unless the series field is quite weak, it is sometimes difficult to start a differential-compound motor. At the time of starting the first rush of current passing through the series field may cause the series-field ampere-turns to be equal to, or even greater than, the shunt-field ampere-turns. This will prevent starting or may even cause the motor to start rotating in the wrong direction. To overcome this difficulty, the series field should be short-circuited during the starting period.

Questions. 1. What are some of the commercial applications of the cumulative-compound motor?

2. Of the differential-compound motor?

40. Speed control of a shunt motor. The speed equation of a shunt motor is as follows:

$$N = \frac{V - i_a r_a}{\Phi Z'}.$$

Inspection of this formula reveals the fact that there are four possible ways of regulating the speed; namely, by varying the impressed difference of potential V, by varying the resistance in series with the armature, by varying Φ, or by varying Z'.

Difference-of-potential control. This method is used to a limited extent. The chief objection to the scheme is that it is difficult to obtain a very large range of potential differences. Where uniform gradation of speed is required the Ward-Leonard system may be used. This requires that the motor whose speed is to be regulated be separately excited from the main supply lines, and that its armature be supplied from an auxiliary generator, the latter being driven at constant speed by a shunt motor which is driven from the line. The field of the generator is excited from the supply lines and may be varied from zero to a maximum in either direction. The above method is expensive, but it is very effective.

Rheostatic control. A resistance is inserted into the armature circuit in this method. A motor used in this way has poor speed regulation; that is, the speed will change considerably as the motor is loaded from no load to full load. This method is inefficient due to power loss in the rheostat. It is recommended only where an occasional change in speed is desired.

Flux control. This is the commonest way of varying the speed of a shunt motor. The usual method requires a variable resistance to be inserted in series with the shunt field. The interpole motor affords means whereby a wide speed range is possible with the field-control method. A common ratio of maximum speed to minimum speed is 3 to 1.

The field flux Φ can also be varied by changing the reluctance of the magnetic circuit. This has been accomplished in two ways. The Lincoln motor is so constructed that the armature core is conical, and as the armature is moved endwise by means of a hand wheel, the air-gap length is increased, and the effective length of the armature conductors shortened. Both of these changes tend to increase the speed. Speed variation in the Stow multi-speed motor is accomplished by plungers which are moved in and out of the hollow pole cores by means of a hand wheel and bevel gears. The first cost of the two abovementioned motors is high, but the operating characteristics are very good.

Z' control. The fourth method of varying the speed of a shunt motor is very seldom used. Z' contains factors representing the number of poles p, the number of conductors Z, and the number of armature paths a. The factor p cannot be changed without making the first cost high. To change the last two factors means changing the armature winding in some way, or having more than one armature winding. Owing to the high first cost, this is seldom done.

41. Speed classification of motors. *Constant-speed motor.* A constant-speed motor is one whose speed does not vary greatly with load when the motor is driven from constant-voltage mains. The shunt motor is an example of this type of motor.

Varying-speed motor. A varying-speed motor is one whose speed varies considerably with load, ordinarily decreasing when the load increases. The series motor is an example of this type of motor.

Adjustable-speed motor. An adjustable-speed motor is one in which the speed can be varied gradually over a considerable range, but when once adjusted the speed remains practically unaffected by load. A shunt motor designed for considerable range of speed adjustment is an example of this type.

42. Regulation. In constant-speed motors the regulation is the ratio of the change in speed between full-load and no-load to the full-load speed, terminal rated difference of potential being held constant.

EXPERIMENT 4-H

Speed Control of Shunt Motors

Object. To study the various methods for controlling the speed of a direct-current shunt motor.

Reference. Langsdorf, "Principles of Direct-Current Machines," Chap. VII.

Apparatus. A Lincoln or Stow type of shunt motor. (If one of these motors is not available an ordinary shunt motor can be used, omitting such parts of the experiment as apply only to the special motor.) Suitable rheostats for controlling field and armature currents.

Method. 1. Connect the motor to a proper source of power, placing rheostats in the armature and field circuits. Maintaining a constant difference of potential at the terminals of the armature and a constant field current, take readings of the speed for various positions of the hand wheel, going from the extreme low-speed position to the extreme high-speed position. Plot curves of speed, armature current, and armature input as ordinates and revolutions of the hand wheel as abscissas.

2. Turn the hand wheel to the low-speed position, maintain constant potential at the armature terminals, and take readings of armature potential, armature current, field current, and speed, varying the field current so as to get the same speed range as in part 1. Plot curves, using speed, armature current, and armature input as ordinates and field current as abscissas.

3. Turn the hand wheel to the high-speed position, maintain constant field current, and reduce the difference of potential across the armature by steps, taking readings at each step. Continue reducing the potential until the motor stops. Plot curves

of speed, armature current, and armature input as ordinates, and difference of potential across the armature as abscissas.

Precautions. Never allow the speed of the motor to go more than 10 per cent above the high-speed rating. Be sure that steady conditions have been reached before taking readings.

Questions. 1. What are the relative advantages of these three methods of speed control? An answer to the above question should include a discussion of relative first costs of machines, relative losses, and relative efficiencies.

2. What limits the maximum speed at which a given machine can be operated?

3. What limits the ratio of high to low speed in each of the three methods of speed control?

CHAPTER V

DIRECT-CURRENT GENERATORS

43. Fundamental principles. The action of a dynamo as a generator is as follows: When a conductor l centimeters in length is forced by some external source of mechanical power to move with a velocity of v centimeters per second at right angles across a magnetic field having a density of B lines of induction per square centimeter, an electromotive force is induced in the conductor. The electromotive force will be equal to $\frac{d\Phi}{dt}$ or Blv abvolts.

If the conductor is a portion of a closed circuit, a current will flow and, according to Ohm's law, the current will be

$$\bar{I} = \frac{\bar{E}}{\bar{R}},$$

where $\bar{I}$ = the current in abamperes,

$\bar{E}$ = the electromotive force in abvolts,

and $\bar{R}$ = the resistance in abohms.

The conductor is now a current-bearing conductor immersed in a magnetic field, and as a result there is a force set up which opposes the motion of the conductor. The force produced, F, equals $Bl\bar{I}$ dynes.

Work is done by the external mechanical agent at the rate of Fv ergs per second in moving the conductor against the opposing force F.

The rate of energy expenditure, or the power developed, in ergs per second, equals Fv or $Bl\bar{I}v$ or $\bar{E}\bar{I}$.

Now,

$$1 \text{ volt} = 10^8 \text{ abvolts},$$
$$0.1 \text{ abampere} = 1 \text{ ampere},$$
$$1 \text{ joule} = 10^7 \text{ ergs},$$

and

$$1 \text{ watt} = 1 \text{ joule per second}.$$

Therefore mechanical power is being expended at the rate of EI joules per second or EI watts, where

$E =$ the electromotive force in volts,

and $I =$ the current in amperes.

The simple generator is a dynamo which absorbs mechanical power at the rate of Fv ergs per second, and transforms that power into electrical power at the rate of $\bar{E}\bar{I}$ ergs per second. (It is assumed that there is no windage or friction.)

Practically all standard forms of direct-current generators as well as direct-current motors consist of a wire-wound or bar-wound armature arranged to rotate between inwardly projecting poles of alternate polarity. Each of the conductors is the seat of an electromotive force which changes its direction each time the conductor passes from one pole to the next pole. The function of the commutator is to convert this internal electromotive force into a unidirectional difference of potential across the armature terminals.

EXPERIMENT 5–A

A Study of Generator Operation

Object. To study the action involved in the conversion of mechanical energy into electrical energy.

Reference. Langsdorf, "Principles of Direct-Current Machines," Chap. II.

Apparatus. A dynamo which can be separately excited and rotated by hand. Fuse wire. Lamp cord. A low-voltage incandescent lamp.

Method. 1. Turn the armature of the dynamo by hand and note the effort required.

2. Connect the field to a suitable direct-current supply so that it can be excited to full strength. Again rotate the armature by hand and note any difference in the effort required.

3. Rotate the armature rapidly by hand, then suddenly short-circuit the armature terminals with a piece of copper wire. Note the result.

4. Turning the armature by hand, determine the largest size of fuse wire which can be melted when connected across the armature terminals.

5. Take a single strand of copper wire from a piece of lamp cord and connect it across the armature terminals. Turn the armature by hand and note results.

6. Connect a low-voltage incandescent lamp across the armature terminals and note the power required to light the lamp to about normal brilliancy.

Questions. 1. Does the armature turn harder when the field is excited or unexcited? Why?

2. Why is it impossible to rotate the armature rapidly when the terminals are short-circuited?

3. Why does the small copper wire become red-hot while the fuse wire does not?

44. Armature windings. There are three classes of armature windings. These three classes are: ring armatures, drum armatures, disc armatures. The drum armature is used to the practical exclusion of the others.

The entire winding on the drum armature is external to the core. Each wire or bar, wound on the outer surface in a direction parallel to the shaft, is connected to another wire or bar by means of a connecting wire which does not thread through the center of the core.

The windings for direct-current generators and motors are nearly always closed windings; that is, windings in which the starting point will finally be reached after having passed through all, or some sub-multiple, of the total number of conductors.

Closed windings for drum armatures are either the lap or the wave type. An element of an armature winding is defined as that portion of a winding which, beginning at a commutator segment, ends at the next commutator segment encountered in tracing through the winding. In the lap winding the successive elements lap back over each other, and in the wave winding the elements progress continuously in wave fashion around the periphery of the armature.

In both the lap and wave windings the two sides of a coil or element are subjected to the influence of adjacent poles of opposite polarity, so that the electromotive forces generated in the two sides are additive.

Fig. 28 represents a simplex lap winding for a four-pole dynamo. There are nine commutator bars and nine winding elements represented in the figure. It will be noted that each element consists of an almost closed loop or coil, and that one element laps over another.

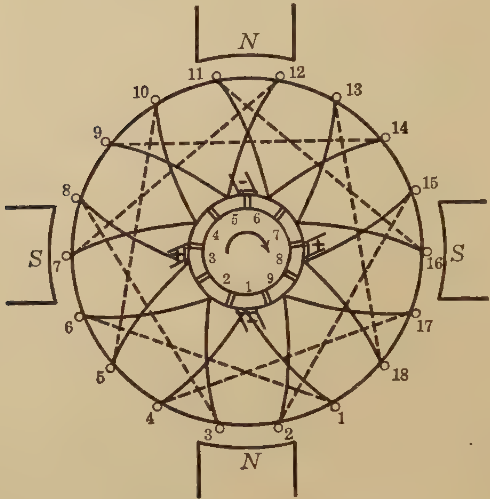

FIG. 28. Simplex lap winding

Z = number of inductors = 18,
p = number of poles = 4,
y_1 = back winding pitch = + 5,
y_2 = front winding pitch = − 3,
y = commutator pitch $= \dfrac{y_1 + y_2}{2} = \dfrac{5-3}{2} = 1,$
and a = number of armature paths = 4.

Fig. 29 represents a simplex wave winding for a four-pole dynamo. There are nine commutator bars and nine winding elements represented in the figure.

$Z = 18,$
$p = 4,$
$y_1 = +5,$
$y_2 = +5,$
$y = \dfrac{y_1 + y_2}{2} = \dfrac{5+5}{2} = 5,$
and $a = 2.$

If two identical simplex lap windings, such as the simplex lap winding represented in Fig. 28, as well as the corresponding commutator bars, are interleaved, the resultant winding

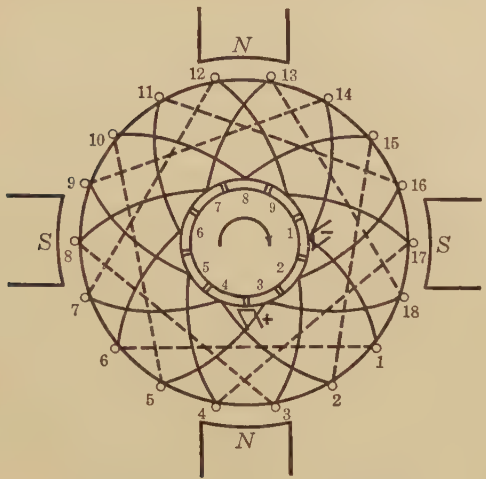

FIG. 29. Simplex wave winding

would be called a duplex lap winding. If three identical simplex lap windings and the corresponding commutator bars are interleaved, the result would be called a triplex lap winding. Duplex, triplex, and higher degree of multiplicity windings are called multiplex windings.

The above paragraph applies to wave windings as well as to lap windings.

A closed armature winding is said to be singly reëntrant if all the inductors are internally connected together. A simplex winding is singly reëntrant. A multiplex winding may or may not be singly reëntrant.

An armature winding is said to be doubly reëntrant if there are two distinct interleaved parts to the armature winding and the two parts are internally insulated from each other. A duplex winding may be singly reëntrant or doubly reëntrant.

An armature winding is said to be triply reëntrant if there are three distinct interleaved parts to the armature winding and the three parts are internally insulated from each other. A triplex winding may be singly or triply reëntrant.

The various winding rules may be briefly stated as follows.

45. Lap windings. 1. The number of winding elements or commutator segments S may be any number, even or odd, consistent with the condition that it must satisfy the relation

$$S = \frac{Z}{2 \times \text{number of turns per element}},$$

and Z must satisfy the relation

$$E = \frac{p\Phi ZN}{a \times 60 \times 10^8}.$$

2. The pitches y_1 and y_2 expressed in terms of coil edges spanned must be odd numbers. They must be approximately $\frac{2S}{p}$. They must have opposite signs.

3. The numerical difference between the winding pitches must be 2 for simplex windings, 4 for duplex windings, 6 for triplex windings, etc.

4. The commutator pitch will be 1 for simplex windings, 2 for duplex windings, 3 for triplex windings, etc.

5. The number of armature circuits in parallel will equal the number of poles times the degree of multiplicity.

6. The degree of reëntrancy is single in simplex windings. It will be double for duplex windings if S is even, and single if S is odd. It will be triple for triplex windings if S is a multiple of 3, and single if S is not a multiple of 3.

46. Wave windings. 1. The number of winding elements or commutator segments S must satisfy the condition

$$S = \frac{Z}{2 \times \text{number of turns per element}},$$

and Z must satisfy the relation

$$E = \frac{p\Phi ZN}{a \times 60 \times 10^8},$$

and in addition S must satisfy the equation

$$y = \frac{2S \pm a}{p},$$

where y must be an integer.

2. The winding pitches y_1 and y_2 must be odd numbers. They must have like signs and they must be approximately equal to $\frac{2S}{p}$. Their average must be equal to the commutator pitch.

3. The number of armature circuits a equals two times the degree of multiplicity.

4. The degree of reëntrancy is single for simplex windings. It is double in duplex windings if y is an even number, and single if y is an odd number. It is triple in triplex windings if y is a multiple of 3, and single if y is not a multiple of 3.

47. A comparison of lap and wave windings. There must be as many brush sets as there are poles for a lap-wound armature. There are usually as many brush sets as there are poles for a wave-wound armature, but only two brush sets (one positive set and one negative set) may be used if the commutator is lengthened to accommodate the required brush-contact surface. The number of paths through a wave-wound armature is the same when two brush sets or p brush sets are used.

The wave winding has equal electromotive forces induced in all the armature paths, even though the armature may not be exactly centered, or even if for any reason the flux entering the armature from one pole is greater than that from another. On the other hand, any unbalancing of the flux in a lap-wound armature will cause the electromotive forces per path to differ, and as a result there may be produced local currents through the armature paths, brush contacts, and the connections that tie together the brush sets of like polarity. These local currents may be prevented from flowing out through the commutator and through the brush connections, by making permanent low-resistance cross connections in the armature winding between equipotential points. This improves commutation since the current through the brush contacts is lessened. These low-resistance ties are called equalizer connections, and they are used in large lap-wound armatures. (The local currents in the armature winding will be increased if the connections are made.)

The selection of an armature winding (lap or wave) is largely an economic problem. The copper required for the two windings will be the same for a given case (neglecting equalizer connections for large lap-wound machines), but the number and size of the conductors will differ. Therefore, the labor cost for construction must be taken into consideration. In general, lap windings are used for low-voltage, high-current machines, and wave windings are used for high-voltage, low-current machines. Between the two extremes there are many sizes where one winding will serve as well as the other from the standpoint of first cost and operation.

Most lap and wave armature windings are simplex. Multiplex windings can sometimes be used to advantage for cutting down the cross section of conductors when relatively large currents are to be handled. This may cut down the labor cost for construction.

EXPERIMENT 5–B

A Study of Armature Windings

Object. To study different types of armature windings by means of winding diagrams and winding models.

References. Langsdorf, "Principles of Direct-Current Machines," Chap. III; Christie, "Electrical Engineering," Chap. VII.

Apparatus. Special winding models, or the core and commutator of an old armature from which the windings have been removed. It is preferable to have at least two winding models, one with an even number of slots and one with an odd number of slots. Balls of string of several different colors.

Method. Several winding diagrams should be prepared before the regular laboratory period. The data for these diagrams should be supplied by the instructor and should be such that the windings can be reproduced on the models available. The winding diagrams should cover four-pole and six-pole machines, lap and wave windings, both simplex and multiplex.

The work in the laboratory will consist of reproducing the winding diagrams on the armature models, using colored string to represent the wire. Strings of different colors are valuable in reproducing multiplex windings in order to clearly distinguish between the different groups of inductors.

Questions. 1. What are the relative advantages of lap and wave windings?

2. For a generator of given rating, which type of winding would require the larger amount of copper?

3. What are the advantages of drum armatures?

4. What advantages result from the use of toothed instead of smooth cores?

5. Give the advantages and disadvantages of semiclosed slots?

EXPERIMENT 5-C

Brush Setting

Object. To set the brushes of a dynamo on the no-load electrical neutrals.

Apparatus. A dynamo. A ballistic galvanometer or millivoltmeter. An ammeter and a voltmeter. Suitable equipment for operating the dynamo as a generator and as a motor.

Method. Place the ammeter in the field circuit and arrange a snap switch in parallel with a resistor so that the field current can be changed quickly. Change the field current by the same amount each time. Place the leads of the ballistic galvanometer or millivoltmeter on adjacent commutator bars. Take readings of the maximum deflections caused by a definite change of field current. (It is preferable to take the readings when opening the switch rather than when closing the switch.) By gradually moving the meter leads along the commutator and keeping the leads on adjacent bars a complete set of readings can be obtained for the whole commutator. The electrical neutrals will be located where the deflections are the greatest; there will be an electrical neutral for each group of brushes. The brushes may then be set at these electrical neutrals.

These electrical neutrals may be checked by placing the brushes on the newly found positions and driving the machine as a generator without load. Note the difference of potential across the brushes. Then shift the brushes slightly, first clockwise and then counterclockwise. If the difference of potential decreases when the brushes are shifted in either direction, the newly found positions are the electrical neutrals.

The electrical neutrals can also be checked by operating the dynamo as a motor without load. Note the speed at which the motor operates. Then reverse the direction of rotation and, keeping the armature difference of potential and field current the same as before, again note the speed at which the motor operates. If the two speeds are the same, the brushes are on the electrical neutrals. If the two speeds are not the same, shift the brushes until the two speeds are the same.

Precautions. Lift the brushes during the first part of the test. This will avoid field distortion due to the brushes short-circuiting armature coils. It will also avoid the possibility of

damaging the millivoltmeter or ballistic galvanometer if the leads should accidentally touch the brushes.

Curves. Plot a curve with maximum deflections as ordinates and meter-lead positions as abscissas. Mark the electrical neutrals.

Questions. 1. Why should the electrical neutrals correspond with the positions where the largest maximum deflections are obtained in the first part of the experiment?

2. Where are the mechanical or geometric neutrals?

3. Why should the generator no-load difference of potential be a maximum when the brushes are set on the electrical neutrals?

4. Why should the no-load motor speeds be the same for both directions of rotation when the brushes are set on the electrical neutrals?

48. The magnetization curve. The armature core, teeth, air gap, pole face, pole core, and yoke make up the magnetic circuit of a dynamo. A field winding is placed on each pole core, and a magnetomotive force is produced by sending current through the field winding. The flux per pole Φ equals the magnetomotive force divided by the reluctance of the magnetic circuit.

The armature winding cuts the flux and an electromotive force is produced. The difference of potential across the armature terminals at no load is

$$V \text{ (no load)} = \frac{p\Phi ZN}{a \times 60 \times 10^8} \text{ volts.}$$

Therefore there is a straight-line relation between V (no load) and Φ if N is held constant. The magnetic circuit of a dynamo is made up of a small air gap and a large amount of iron, so that the relation between V (no load) and I_f (field current) is not a straight line. A curve plotted to represent I_f as abscissas and V (no load) as ordinates is commonly called a magnetization curve.

The magnetization curve of a dynamo is useful for determining the operating characteristics of the machine without actually loading it.

EXPERIMENT 5-D

The Magnetization Curve of a Generator

Object. To determine the magnetization curve, or the hysteresis loop, of a direct-current compound-wound generator. To determine the ratio of the number of turns on the shunt field to the number on the series field.

Apparatus. A direct-current compound-wound generator. A motor for driving the generator at rated speed. A starting box and suitable field rheostats.

Method. Arrange to excite the shunt field of the generator from a separate source of supply the difference of potential of which is at least 25 per cent greater than the rating of the generator. Use a rheostat in the field circuit so that the current can be varied from very low values up to the maximum required. A potentiometer (3-point) rheostat is particularly suitable for this purpose. Drive the generator at its rated speed and take readings of field current, induced electromotive force, and speed. A series of such readings should be taken for both increasing and decreasing values of field current so that the complete hysteresis loop can be plotted. If the speed of the generator varies while the readings are being taken, these readings may be reduced to a common-speed basis since the induced electromotive force is directly proportional to the speed of rotation.

Repeat the experiment, using the series field instead of the shunt field. For this part of the experiment it will be necessary to obtain only one half the total hysteresis loop.

Measure the resistances of the shunt and series fields by the drop-of-potential method.

Plot the necessary curves to illustrate your results.

Precautions. In obtaining data for the rising part of the hysteresis loop, care should be taken not to exceed the value of field current desired. If for any reason the desired value is exceeded, the field current should be lowered to the starting point and then increased to the desired point. In taking readings for the descending side of the loop, similar precautions are necessary. If the field current is ever reduced below the desired point, it should be increased to its maximum value and then reduced to the desired point.

Questions. 1. Explain why the curve obtained may be called the magnetization curve?

2. What determines the slope of the magnetization curve before the bend in the curve is reached?

3. From your data, determine what resistance must be placed in series with the shunt field in order to obtain rated difference of potential at the terminals when the machine is self-excited.

4. What would the terminal difference of potential be if no resistance were placed in series with the shunt field?

5. What would be the rating of a field rheostat suitable for use with this generator?

6. Explain why the precautions mentioned are necessary.

49. The building up of a self-excited generator. The field current of a self-excited generator is supplied from the machine's own armature. A self-excited generator may have a shunt field, a series field, or both shunt and series fields.

When a self-excited generator is normally operated and then stopped, the flux per pole reduces to a small value which is commonly called the residual flux. On starting the machine again a small electromotive force is induced in the armature winding due to the cutting of the residual lines of induction. The induced electromotive force produces a small field current, which in turn strengthens the residual magnetism. In turn, the electromotive force increases, and correspondingly the field current is increased. This process is known as the "building up" of the generator, and it continues until the stable operating difference of potential across the generator terminals is reached.

If the machine has no residual magnetism it cannot build up. To get the machine to build up, it is necessary to momentarily send current through the field windings from some outside source. This process will leave residual magnetism so that the machine will build up when it is properly operated as a self-excited generator.

The field current of a self-excited generator must be in such a direction that the resulting magnetomotive force tends to strengthen the residual magnetism, as otherwise the machine will not build up. The generator will not build up if the armature speed is too low, or if the field-circuit resistance is too high.

EXPERIMENT 5-E

The Building Up of a Self-excited Shunt Generator

Object. To investigate the influence of the direction of rotation, the speed of rotation, and the resistance of the field circuit on the building up of a shunt generator.

Reference. Langsdorf, "Principles of Direct-Current Machines," Chap. VI.

Apparatus. A dynamo which can be used as a self-excited shunt generator. An adjustable-speed motor for driving the generator at different speeds. A suitable starting box and the necessary field rheostats.

Method. 1. With the field disconnected from the armature, drive the generator at its rated speed. Observe the difference of potential across the armature terminals. Connect the shunt field directly to the armature terminals and observe the difference of potential across the armature terminals. Reverse the shunt field and again observe the difference of potential. Reverse the direction of rotation of the generator and repeat the above.

2. With the shunt field connected directly to the armature in such a way that the generator will build up, determine the minimum speed of the generator which will cause it to build up. Insert some resistance in series with the shunt field and again determine the minimum speed which will cause the generator to build up.

3. With the generator running at rated speed, determine the maximum resistance which can be placed in series with the shunt field without preventing the generator from building up.

Questions. 1. It becomes necessary to reverse the direction of rotation of a shunt generator without changing the polarity of its brushes. Show by means of diagrams how this can be accomplished.

2. A shunt dynamo has been used as a motor running in a clockwise direction. It is desired to use the dynamo as a generator. In which direction should it be driven so as to build up without any change in connections being necessary?

50. Brush-contact resistance. The resistance of the brush contact decreases with increasing current. If carbon brushes are used, the drop of potential across the contact will be from 1 to

1.25 volts when brush-contact current densities of 35 or 40 amperes per square inch are used. The drop of potential increases very slowly for higher values of current density, and decreases somewhat for lower current densities.

The rules of the American Institute of Electrical Engineers specify that a brush-contact drop of 1 volt at each brush set, or a drop of 2 volts for the entire machine, without regard to the amount of current flowing, should be used for ordinary machines with carbon brushes, when losses are being estimated for computing the conventional efficiency.

51. Load tests. *Series generator.* The series generator is so constructed that the field winding is in series with the armature. Therefore the current in the armature is likewise the current in the field winding. It follows that (within limits) an increase in load (decrease in external resistance) causes an increase of excitation, and also an increased generated electromotive force, the speed being kept constant.

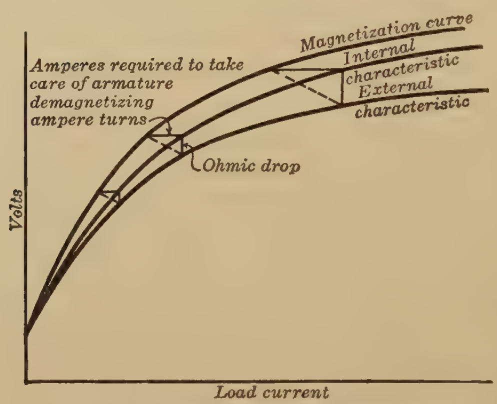

FIG. 30. Characteristic curves of a series generator

If the machine is loaded and readings taken so that a curve can be plotted between the terminal difference of potential V and line current I, the resultant curve is called the external characteristic for the generator.

An external characteristic curve for a series generator begins with a small value of V, for I (current) $= 0$, due to the residual magnetism. The curve rises as I is increased and after reaching a maximum droops more and more. Then it bends downward sharply and strikes the I axis. The curve differs from the magnetization curve due to the ohmic drop in the armature and the series field, and to armature reaction.

The internal characteristic shows the relationship between the induced electromotive force and the armature current.

Fig. 30 represents the magnetization curve, internal characteristic, and external characteristic for a series generator.

Shunt generator. Fig. 31 represents the external and internal characteristic curves of a shunt generator.

The external characteristic curve shows the relation between terminal difference of potential and line current. The internal characteristic curve shows the relation between induced electromotive force and armature current.

The terminal difference of potential V of a shunt generator decreases as the load is increased, for three reasons. First, the ohmic drop decreases V; second, when the brushes are properly set armature reaction causes Φ to be decreased, with the result that the induced electromotive force and V are reduced; third, when the terminal difference of potential is decreased, the field current and the corresponding magnetomotive forces are lessened, with the result that the electromotive force and the terminal difference of potential are still further reduced.

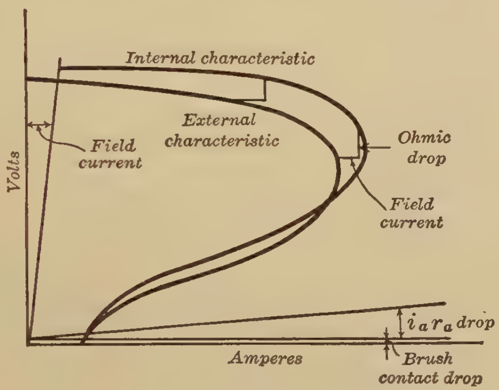

FIG. 31. Characteristic curves of a shunt generator

It will be noted that the current reaches a maximum for the characteristic curve and then decreases. This maximum value is relatively large for moderate-sized and large-sized generators, so that the machine may be seriously damaged if an attempt is made to obtain data for the whole external characteristic curve. With a comparatively small machine, having a relatively large armature reaction, data may be obtained for the whole external characteristic without causing excessive heating or sparking at the brush contacts.

Compound generator. The compound generator is a combination of the shunt and series generators. The generator is constructed with a series field as well as a shunt field. In designing

the machine the number of ampere-turns for the series field may be varied with reference to the shunt-field ampere-turns. The series field may be so connected that its magnetomotive force adds directly to the magnetomotive force of the shunt field. This connection makes a cumulative compound generator. The generator is differentially compounded if the series field is so connected that the two magnetomotive forces are in opposition.

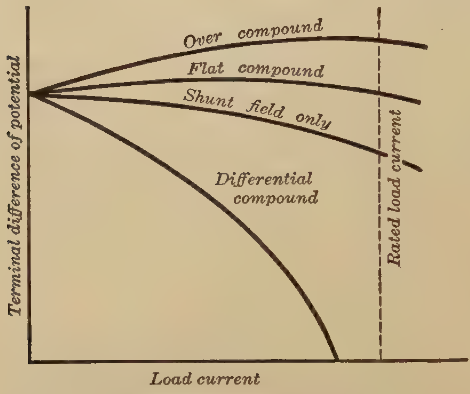

FIG. 32. Effects of series field winding on the external characteristic of a generator

Fig. 32 represents external characteristic curves for a shunt generator and a compound generator with the series field connected for differential and for cumulative results. The number of turns on the series field controls the degree of compounding shown in the figure.

52. Regulation. The regulation was formerly defined as the difference between the full-load and no-load terminal voltages, divided by the full-load terminal voltage. The percentage voltage regulation was the above ratio multiplied by 100. The regulation is now stated by giving the numerical values of the voltage at no load and rated load. The above definitions apply only to generators designed for constant voltage.

EXPERIMENT 5–F

The External Characteristic of a Shunt Generator

Object. To determine the external characteristic curve of a shunt generator. To derive from this the total or internal characteristic curve. To determine the voltage regulation of the machine.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. X.

Apparatus. A shunt generator and a suitable motor for driving it at constant speed. The necessary field and loading rheostats.

Method. 1. Drive the generator at rated speed. Adjust the shunt-field rheostat so that the generator will have rated terminal difference of potential at no load. Holding speed and shunt-field resistance constant, gradually reduce the resistance of the external circuit from open-circuit to short-circuit. At each step take readings of terminal difference of potential, load current, field current, and speed. Then continue the test by gradually increasing the external resistance from short-circuit to open-circuit. Take readings as before. Plot the curve of terminal difference of potential as ordinates and the corresponding load currents as abscissas.

2. Adjust the shunt-field rheostat and the load resistance so that the rated terminal difference of potential will be produced at rated full load and rated speed. Holding shunt-field resistance and speed constant, take readings of terminal difference of potential, load current, field current, and speed as the load is changed by steps from 25 per cent overload to zero. Plot the external characteristic curve.

3. Measure the resistance of the armature circuit exclusive of the brush-contact drop.

4. Derive graphically the total or internal characteristic curve.

5. Determine the percentage regulation of the generator.

Precautions. Do not open the external circuit while a curve is being taken. If this is done near the critical point and the circuit again closed, a very heavy first rush of current will result. This may do considerable damage. In any case, the data will be impaired. When these observations are made for commercial purposes the machine should be at normal operating temperature.

Questions. 1. What is meant by "good regulation"?

2. Name a commercial application where poor regulation is desirable.

3. Why do the external characteristic curves for increasing and decreasing values of load current differ?

4. Explain fully why a heavy first rush of current will result if the external circuit is opened near the critical point on the curve, and then again closed.

EXPERIMENT 5-G

The External Characteristic of a Compound Generator

Object. To obtain the external characteristic curve of a compound-wound generator and to study means of changing the degree of compounding.

Apparatus. A compound-wound generator having a rising characteristic (over-compounded). A motor for driving the generator at its rated speed. The necessary field and loading rheostats.

Method. 1. Drive the generator at its rated speed and adjust the shunt-field rheostat until rated difference of potential is obtained at no load. Then, maintaining speed and shunt-field resistance constant, vary the load in steps from zero to 125 per cent of full-load rating. Take readings of terminal difference of potential, load current, shunt-field current, and speed. Plot the external characteristic curve.

2. Place an adjustable resistance shunt across the series field. Adjust the shunt-field rheostat so that the generator will have rated terminal difference of potential at no load. Then load the machine to its rated capacity, maintaining its rated speed. Now adjust the series-field shunt until the terminal difference of potential at full load is equal to the terminal difference of potential at no load (flat-compounded). Leaving these adjustments fixed, vary the load by steps from zero to 125 per cent of rated full load and take readings of terminal potential, load current, shunt-field current, and speed. Plot the external characteristic curve.

Questions. 1. Can a generator be compounded to compensate for speed changes of the prime mover caused by changes in load?

2. What is the effect upon the external characteristic curve of a compound generator if the generator is driven above or below its rated speed, the comparisons being made on the basis of shunt-field rheostat adjustments for equal no-load potentials?

53. Shunt generators in parallel. When two or more shunt generators are connected in parallel, their operation is stable. Two shunt generators connected in parallel are represented in Fig. 33. It will be noted that the difference of potential across

the two machines will be the same at all times. Any tendency which causes one generator to lose its proper share of current will result in a slightly greater induced electromotive force in its armature, due to the decreased armature reaction. The net result is that the original conditions will be restored, assuming that the prime movers operate the generators at practically constant speed.

It is not necessary that the generators to be connected in parallel should have the same ratings. If the shapes of the

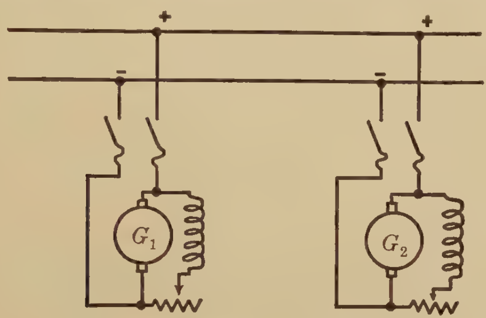

FIG. 33. Two shunt generators connected in parallel

external characteristics for the different machines (terminal difference of potential versus percentage full-load current) are identical, the machines will divide the load properly in proportion to their respective ratings.

EXPERIMENT 5-H

The Operation of Shunt Generators in Parallel

Object. To operate two shunt generators in parallel and to study the division of load between them.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. XI.

Apparatus. Two shunt-wound direct-current generators. Two motors suitable for driving the generators at their rated speeds. The necessary rheostats.

Method. Drive the two generators at their rated speeds and adjust the field rheostats so that they have the same difference of potential at their terminals. Place the two generators in

parallel by connecting their positive terminals together and their negative terminals together. Maintain the speeds constant and load the machines to their rated capacities. Adjust the shunt-field rheostats so as to obtain the proper division of load between the two machines and the rated difference of potential at full load. Having made these adjustments, maintain the speeds and the shunt-field resistances constant and vary the load from 125 per cent of the combined rating of the two machines to zero. Take readings of total load current, the load current delivered by each machine, the terminal difference of potential, and the speeds.

If the division of load between the two machines is not proportional to their ratings, see if this division of load can be improved by adding a little resistance in series with the armature of the machine having the better voltage regulation. Repeat the readings taken above.

In commercial operation it is necessary to perform the various operations with as little disturbance to the system voltage as possible. Place a load on one machine and practice paralleling the other machine with it without disturbing the terminal difference of potential. Practice shifting the load from one machine to the other without varying the terminal difference of potential.

Precautions. The maintenance of constant speed is important because speed changes may materially affect the distribution of load. In paralleling generators for the first time, care must be taken to see that the polarities of the two machines are the same.

Question. Why is the parallel operation of generators desirable?

54. Compound generators in parallel. Two or more compound generators with rising external characteristics will not have stable operation if they are connected in parallel unless the series fields are provided with equalizer connections as shown in Fig. 34. If the machines have drooping (differential-compound) characteristics the equalizer connection is not necessary.

The use of the equalizer connection does not insure a proper division of load.

If two compound generators have identical external characteristics (terminal difference of potential versus percentage full-load current), and if the resistances of the series field wind-

ings are inversely proportional to the current ratings of the two generators, the two generators will divide the load in proportion to their ratings.

If the machines do not have identical external characteristics, a variable resistance can be placed in series with the series

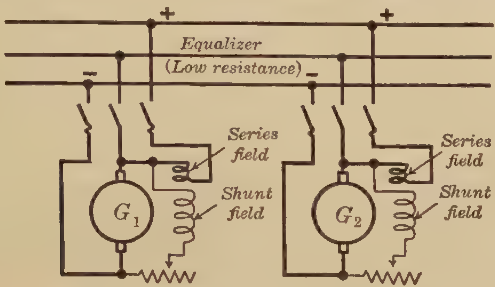

FIG. 34. Two compound generators connected in parallel

field of the generator having the more rising characteristic. As the resistance is increased, a greater percentage of the load will be shifted over to the other machine. At a particular value of resistance the machines will divide the load properly. The resistances of the series-field circuits will not necessarily be inversely proportional to the respective machine ratings when the load has been properly divided.

EXPERIMENT 5–1

The Operation of Compound Generators in Parallel

Object. To operate two cumulatively compound generators in parallel. To make such adjustments as are necessary in order to produce the proper division of load between the two generators.

Apparatus. Two compound-wound generators, preferably of different sizes and having different external characteristics. Two motors for driving the above generators. The necessary starting boxes and field rheostats.

Method. 1. Drive the two generators at their rated speeds and adjust the shunt-field rheostats so that the two machines will have the same terminal difference of potential at no load. Place the two machines in parallel without using the equalizer connection. Note the result.

2. Make the proper equalizer connection and again parallel the two generators. Gradually load the generators and after each increment of load take readings of total load current, the load current supplied by each machine, the equalizer current, the terminal difference of potential, and the speed of each machine.

3. Place a suitable variable resistance in series with the series field of the generator having the more rising external characteristic. Adjust the shunt-field rheostats until the two generators have the same induced electromotive forces. Maintain constant speeds and constant shunt-field resistances. Load the machines and adjust the series-field resistance until the proper division of load is obtained with each machine loaded to its rated capacity. Take a set of readings similar to those taken above.

Precautions. Be sure that both generators are connected cumulatively and not differentially. The series fields must be connected to armature terminals having the same polarity; that is, both on the positive side or both on the negative side. If this is not done each series field constitutes a short circuit for the armature of the other machine. It is desirable that the equalizer connection be of relatively low resistance. The inserting of resistance in series with the series field of one machine reduces its series-field current and correspondingly increases the series-field current of the other machine. This should not be carried so far as to overheat the series-field winding of the second machine.

Questions. 1. What would be the effect of shunting the series field of the machine having the higher degree of compounding?

2. What would be the effect of reducing the speed of the machine having the higher degree of compounding, shunt-field currents being adjusted for equal no-load voltages?

3. What would be the result of adding resistance in the equalizer circuit?

CHAPTER VI

EFFICIENCY, REGULATION, AND HEATING

55. Direct-current dynamo losses. A part of the energy supplied to any motor or generator is lost within the machine itself. The loss of energy should be kept low for two reasons. First, the lost energy is wasted and therefore it represents an economic loss; second, the lost energy increases the temperature of the machine and so limits its output.

Dynamo losses may be divided into the following parts:

1. Copper Losses in
   a. Armature winding,
   b. Interpole winding,
   c. Shunt winding,
   d. Series winding.
2. Iron Losses due to
   a. Hysteresis in armature core and in pole shoes,
   b. Eddy currents in armature core and in pole shoes.
3. Friction Losses due to
   a. Bearing friction,
   b. Brush friction,
   c. Windage.
4. Additional Losses in
   a. Brush contacts,
   b. Shunt-winding rheostat,
   c. Series-winding shunt,
   d. Interpole-winding shunt,
   e. Armature-winding due to eddy currents.

The copper losses may be readily calculated.

The armature-winding copper loss is equal to $I_a^2 r_a$ watts, where

I_a = armature current in amperes,

and r_a = armature-winding resistance in ohms.

The interpole-winding copper loss is equal to $I_i^2 r_i$ watts, where

I_i = interpole-winding current in amperes,

and r_i = interpole-winding resistance in ohms.

The shunt-winding copper loss is equal to $I_f^2 r_f$ watts, where

I_f = shunt-winding current in amperes,

and r_f = shunt-winding resistance in ohms.

The series-winding copper loss is equal to $I_{se}^2 r_{se}$ watts, where

I_{se} = series-winding current in amperes,

and r_{se} = series-winding resistance in ohms.

The sum of the iron losses, the friction losses, and eddy-current loss in the armature winding may be easily determined for a shunt dynamo by a simple test. The machine is operated as a motor without a load. The field rheostat is adjusted so that the dynamo is operating at the rated or desired speed. The difference of potential across the armature terminals is varied over a range which includes the rated difference of potential. The armature current and the difference of potential across the armature terminals are noted. The input to the armature equals VI_a watts, where

V = difference of potential across the armature terminals.

VI_a = friction loss + $W_e + W_h + I_a^2 r_a$ + brush-contact loss, where

W_e = eddy-current loss in armature core and in pole shoes, and

W_h = hysteresis loss in armature core and in pole shoes.

The brush-contact loss is assumed to be equal to $2\ I_a$ watts. (See Chapter V, § 50.) Then friction loss + $W_e + W_h = VI_a - I_a^2 r_a$ − brush-contact loss. The friction loss + $W_e + W_h$ is equal to EI_a watts, where

E = generated electromotive force in dynamo.

Proof.

$$V = E + I_a r_a + 2.$$
$$VI_a = EI_a + I_a^2 r_a + 2\ I_a.$$
$$EI_a = VI_a - I_a^2 r_a - 2\ I_a \text{ watts.}$$

The iron losses are a function of the induced electromotive force within the machine.

W_e (eddy-current loss in watts) $= k_1 N^2 B^2$,

and W_h (hysteresis loss in watts) $= k_2 N B^{1.6}$,

where k_1 and k_2 are constants,

N = number of revolutions per minute,

and B = flux density.

If N is kept constant,

$$W_e = k_3 B^2 \text{ watts,}$$

and $$W_h = k_4 B^{1.6}, \text{ where } k_3 \text{ and } k_4 \text{ are constants.}$$

The induced electromotive force in the dynamo equals $Z'\Phi N$, where

$$Z' = \text{a constant for the dynamo,}$$

and $$\Phi = \text{flux per pole.}$$

If N is kept constant, the induced electromotive force is proportional to Φ, and is therefore proportional to B.

$$W_e + W_h = k_5 E^2 + k_6 E^{1.6} \text{ watts,}$$

where E = induced electromotive force in volts,
k_5 and k_6 are constants,

and EI_a = friction losses + k_5E^2 + $k_6E^{1.6}$ + eddy-current loss in armature windings.

A curve can be plotted with the products EI_a as ordinates and E as abscissas. Thus for the speed maintained, the friction losses plus the iron losses plus the eddy-current loss in the armature winding can be taken from the curve for any desired value of E. It must be kept in mind that the curve is plotted for a particular value of N and that it must be used accordingly.

The additional losses may be handled in the following manner. The brush-contact loss is assumed to be equal to $2\,I_a$ watts. (See A.I.E.E. Standards, No. 5 (July, 1925), Arts. 5–365.) The shunt-field rheostat loss is equal to $I_s^2 r_r$ watts, where r_r = rheostat resistance in ohms. Since this loss is usually present when operating the machine it is considered as a part of the total machine losses. The shunt-field copper loss plus the shunt-field rheostat loss equals VI_s watts for a shunt or long-shunt compound dynamo. The losses in the series-winding shunt and in the interpole-winding shunt are calculated by the I^2R method. The armature-winding loss due to eddy currents has been included with the iron and friction losses.

56. Conventional efficiency. The conventional efficiency is computed from the following relations:

$$\text{Input} = \text{output} + \text{losses,}$$

and $$\text{output} = \text{input} - \text{losses,}$$

whence the conventional efficiency equals

$$\frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{\text{input} - \text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{input}}.$$

If any one of the above expressions for the conventional efficiency is multiplied by 100, the percentage conventional efficiency is obtained.

57. Direct-current shunt-motor efficiency. Measure the armature resistance by the drop-of-potential method. Operate the machine as a motor without a load. Vary the difference of potential impressed across the armature terminals over a reasonably wide range which includes the rated difference of potential. Hold the speed of the motor constant and at the rated value by adjusting the shunt-field current. For each adjustment of the difference of potential impressed across the armature terminals record the armature current and the field current.

Then, for any set of readings, $E = V - I_a r_a - 2$ volts, and $P_s = EI_a$ watts. In this expression P_s represents windage, friction, and no-load iron losses. A curve may be plotted with P_s as ordinates and E as abscissas.

The efficiency of the motor may be determined for any assumed line current and rated line difference of potential as follows: $I_a = I_{\text{line}} - I_f$. The value of I_f may be determined from the running-light test and it will be the field current of the machine operating at its rated speed with rated difference of potential impressed across its terminals. The value of E for the assumed line current $= V$ (rated value) $- I_a(r_a + r_i) - 2$ volts, where I_a equals the assumed line current minus the shunt-field current. P_s is then taken from the P_s-E curve.

The percentage conventional efficiency will be equal to

$$\left(1 - \frac{\text{losses}}{\text{input}}\right)100 = \left(1 - \frac{P_s + I_a^2 r_a + 2\,I_a + VI_f}{VI_{\text{line}}}\right)100.$$

The resistance r_a in the above equation must be corrected to 75 degrees centigrade. (See A.I.E.E. Standards, No. 5 (July, 1925), Arts. 5–357.)

EXPERIMENT 6–A

The Conventional Efficiency of a Direct-Current Motor

Object. To determine the losses in a direct-current shunt motor and from these to calculate the conventional efficiency of the motor.

Reference. A.I.E.E. Standards, No. 5 (July, 1925).

Apparatus. A direct-current shunt motor, with a suitable starting box and field rheostat.

Method. Make the necessary resistance measurements. Connect the motor and starting box to a suitable source of supply. The difference of potential of the supply should be at least 25 per cent greater than the voltage rating of the motor. Maintaining speed constant at its rated value, vary the impressed difference of potential in steps through as wide limits as possible. At each step take readings of the armature current and the shunt-field current. If the motor is an adjustable-speed motor, obtain the necessary data at both the lowest and highest rated speeds.

Curves. Plot a curve showing the relation between the stray-power loss and the induced electromotive force. Using horsepower output as abscissas, plot the efficiency curve of the motor. On the same curve sheet, also plot the various losses.

Questions. 1. How would the various losses be affected by operating the motor at speeds other than the rated speed?

2. What effect would a change in temperature have on the eddy-current loss?

3. What relation exists between the various losses at the point of maximum efficiency?

4. How does this method of obtaining efficiency compare in accuracy with the brake test?

58. Direct-current generator efficiency. Operate the machine as a shunt motor without load. Vary the difference of potential impressed across the armature terminals over a reasonably wide range which includes the rated difference of potential. Hold the speed of the dynamo constant at the rated value by adjusting the shunt-field current. For each adjustment of difference of potential impressed across the armature terminals record the

armature current and the field current. Measure the armature resistance by the drop-of-potential method.

Then, for any set of readings, $E = V - i_a(r_a + r_i) - 2$ volts, and $P_s = EI_a$ watts. A curve may be plotted with P_s as ordinates and E as abscissas.

The efficiency of the generator may be determined for any assumed line current and the rated line difference of potential as follows: $I_a = I_{\text{line}} + I_f$, E for the assumed line current $= V$ (rated value) $+ I_a(r_a + r_i + r_{se}) + 2$ volts (long-shunt connection). For a shunt generator an approximate value of I_f is assumed in order to obtain a first approximation of E. Then estimate the corrected value of I_f by assuming that I_f is proportional to E over a very short range. It may be necessary to recalculate E.

From the P_s-E curve, determine P_s.

The percentage conventional efficiency will be equal to

$$\left(1 - \frac{\text{losses}}{\text{input}}\right)100$$
$$= 1 - \left(\frac{P_s + I_a^2(r_a + r_i + r_{se}) + 2\,I_a + VI_f}{VI_{\text{line}} + P_s + I_a^2(r_a + r_i + r_{se}) + 2\,I_a + VI_f}\right)100.$$

The resistances in the above equation must be corrected to 75 degrees centigrade. (See A. I. E. E. Standards, No. 5 (July, 1925), Arts. 5–357.)

EXPERIMENT 6–B

The Conventional Efficiency of a Direct-Current Generator

Object. To determine the losses in a direct-current generator, and from these to calculate the conventional efficiency of the generator.

Reference. A. I. E. E. Standards, No. 5 (July, 1925).

Apparatus. A direct-current generator, a suitable starting box, and a field rheostat for operating the generator as a shunt motor.

Method. Drive the generator as a shunt motor at its rated speed and obtain data as outlined in Experiment 6-A.

Curves. Plot curves similar to those called for in Experiment 6-A. Use output in kilowatts instead of horse power.

Questions. 1. How can you determine the shunt-field current necessary to maintain constant terminal difference of potential without actually loading the machine, (*a*) shunt generator, (*b*) compound generator?

2. What is the effect on the various losses if the generator is operated at terminal difference of potential other than the rated difference of potential?

59. Opposition tests. When two machines of about the same size are available, they may be tested by an opposition method. Opposition tests lend themselves readily to temperature-rise determinations. The efficiency and the regulation may also be determined by these methods.

Three different methods of performing opposition tests will be briefly discussed. In each of these methods the dynamos must be mechanically connected. The tests discussed here are called Blondel's, Hutchinson's, and Kapp's opposition methods.

60. Blondel's opposition method. In Blondel's opposition method the electrical loss is supplied electrically, and the mechanical losses as well as the iron losses are supplied mechanically. The wiring diagram for Blondel's opposition test is shown in Fig. 35. The starting boxes and certain field windings have been omitted to simplify the diagram. The auxiliary motor is mechanically connected to armatures No. 1 and No. 2 by means of a belt or flexible coupling. It is assumed that the auxiliary motor has been calibrated.

After the dynamo armatures have been brought to the proper speed by means of the auxiliary motor, the electromotive forces of the armatures No. 1 and No. 2 (dynamos under test) are adjusted so that they are equal to each other in the local circuit. The switches that are shown may then be closed and if the booster electromotive force is equal to zero, the current in the series circuit will be equal to zero. To load the set, it is necessary to have an electromotive force generated in the booster. Assume that an electromotive force is generated in the booster armature and the electromotive forces of all the armatures are in the directions shown in Fig. 35. As a result of the booster electromotive force, current is flowing in the series circuit as shown. Machine No. 1 is then a generator supplying electrical power to machine No. 2. Machine No. 2 is then a motor supply-

ing mechanical power to machine No. 1. If the induced electromotive forces of machines No. 1 and No. 2 are kept the same, the booster is supplying the copper losses to the series circuit and the auxiliary motor is supplying friction and iron losses.

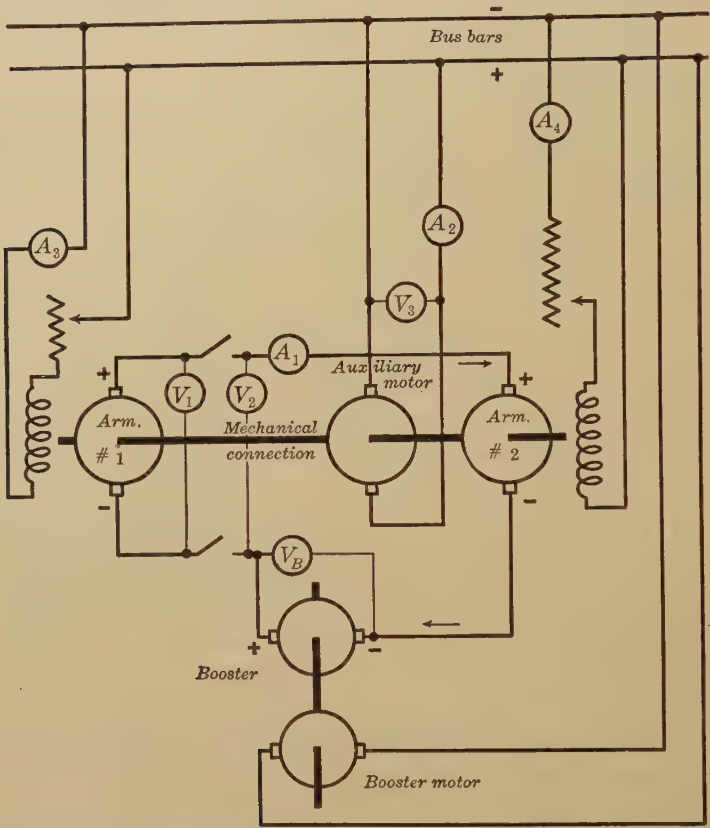

FIG. 35. Blondel's opposition method of testing two direct-current dynamos. (Simplified diagram)

If the two dynamos under test are identical, the losses of each machine will be equal to one half of the outputs of the auxiliary motor and the booster.

61. Temperature rise by Blondel's method. The machines do not need to be identical for this test. It is necessary that the dynamos (auxiliary motor, booster, and running mate) be large enough to accommodate the machine to be tested. The electro-

motive force of the booster and the field currents of machines No. 1 and No. 2 are so adjusted that the machine under test has the rated difference of potential across its armature terminals and the full-load value of current is flowing through its armature. The machine under test should be operated as a motor or generator, depending on its rating.

Before beginning the heat run the resistances of the field winding and the armature winding are measured. (The windings are assumed to be at room temperature.) The machine is then loaded as above stated and the load is maintained until the temperature of the machine is constant, or for a specified number of hours. The hot-winding resistances are then measured. The temperature rise of the copper windings is calculated. The temperatures of the iron parts and the commutator are measured with thermometers.

62. Regulation by Blondel's method. The machines do not need to be identical for this test. It is necessary that the dynamos (auxiliary motor, booster, and running mate) be large enough to accommodate the machine to be tested. The wiring diagram shown in Fig. 35 must be modified, so that the machine acting as a generator is self-excited.

If the machine to be tested is a generator, voltage regulation is desired. The auxiliary motor is adjusted when necessary so that the speed of the generator to be tested is maintained at the rated value during the test. The electromotive forces of machines No. 1 and No. 2 and the booster are so adjusted that the generator has the rated difference of potential across its terminals, and is acting as a generator delivering full-load armature current. Then reduce the booster electromotive force and armature current to zero, and note the generator difference of potential.

The percentage voltage regulation equals the ratio of the difference between the no-load terminal voltage and the full-load terminal voltage to the full-load voltage multiplied by 100.

If the machine is to be tested as a motor, speed regulation is desired. The booster electromotive force is adjusted to give the full-load armature current in the motor. The auxiliary motor speed is varied until the terminal difference of potential across the motor is the rated value. If necessary the motor field current should be modified to give the rated speed for the full-

load condition. After the full-load adjustment is made, reduce the booster electromotive force until the motor armature current is reduced to zero. Then adjust the auxiliary motor speed until the difference of potential across the motor terminals is the rated value. Keep the motor field current constant. The speed of the motor is now the no-load speed.

The percentage speed regulation equals 100 times the difference between the no-load speed and the full-load speed divided by the full-load speed.

63. Efficiency by Blondel's method. The machines must be identical for this test. It is necessary that the dynamos (auxiliary motor and booster) be large enough to accommodate the machines to be tested.

If the machine to be tested is a generator, it must be operated as a generator. The speed must be kept at the rated value by means of the auxiliary motor, and the difference of potential across the terminals of the machine must be kept at the rated value by means of the generator's own field current. If the machines are identical, the field currents of the machines must be kept the same, and consequently the electromotive forces will be kept the same. The armature current is adjusted to a proper value by adjusting the electromotive force of the booster. If the electromotive forces of the identical machines are kept the same, the losses of each machine will be equal to one half of the outputs of the auxiliary motor and the booster.

Let I = circulating current,
I_{fg} = generator field current,
V_g = generator difference of potential,
and V_b = booster difference of potential.

Then for any particular set of conditions the efficiency of the generator is equal to

$$\frac{V_g(I - I_{fg})}{V_gI + \frac{1}{2}V_bI + \frac{1}{2}\,(\text{output of auxiliary motor})}.$$

If the machine to be tested is a motor, it must be operated as a motor. The booster electromotive force is adjusted to give the desired circulating current. The auxiliary motor speed is adjusted to give the rated difference of potential across the motor terminals at all loads. The field currents of the two machines must be kept the same, and at such value as to give the rated

speed at full load. These field currents must be maintained constant throughout the test.

Let $V_m =$ motor difference of potential,
and $I_{fm} =$ motor field current.

Then the efficiency of the motor is equal to

$$\frac{V_m I - \frac{1}{2} V_b I - \frac{1}{2}(\text{output of auxiliary motor})}{V_m(I + I_{fm})}.$$

EXPERIMENT 6-C

Efficiency and Regulation of a Dynamo by Blondel's Opposition Method

Object. To determine the efficiency and regulation of a machine by Blondel's opposition method of testing.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XIV.

Apparatus. Two identical machines, direct-connected preferably. An auxiliary motor whose losses have been determined as in Experiment 6-A. A booster of suitable capacity and a motor for driving the booster. The necessary starting boxes and field rheostats.

Method. Connect the apparatus as indicated in the simplified diagram Fig. 35. Start the auxiliary motor. Adjust the field currents of the machines under test so that their induced electromotive forces are equal. If the dynamos are rated as generators, maintain constant speed by making the necessary adjustments of the auxiliary motor field current. If the dynamos are rated as motors, adjust the field of the auxiliary motor so as to maintain the terminal difference of potential of the machine operating as a motor constant throughout the test. Vary the circulating current by varying the field of the booster. Take readings at various loads from zero to 125 per cent of rating.

Make the necessary changes and determine the regulation of the machines.

Curves. Plot the efficiency and regulation curves of the machine.

64. Hutchinson's opposition method. In Hutchinson's opposition method the auxiliary motor of the Blondel's opposition

method is omitted. The friction and iron losses are supplied electrically from the bus bars. The wiring diagram for the Hutchinson's opposition method is shown in Fig. 36. The starting boxes and certain field windings have been omitted to simplify the diagram.

Dynamo No. 2 is started as a motor. Dynamo No. 1 acts as a generator and its field current is so adjusted that E_1 equals E_2, where

E_1 = induced electromotive force of machine No. 1,
and E_2 = induced electromotive force of machine No. 2.

The relative polarities must be as indicated in Fig. 36. The switches that are shown may then be closed. The amount of current that will circulate in the series circuit will depend upon the electromotive force of the booster and the resistance of the series circuit. If the current flows in the direction shown, dynamo No. 1 will be a generator and dynamo No. 2 will be a motor.

65. Temperature rise by Hutchinson's method. The machines do not need to be identical for this test. It is necessary that the dynamos (booster and running mate) be large enough to accommodate the machine to be tested. It is assumed that the bus-bar difference of potential is equal to the rated difference of potential of the machine to be tested. The machine to be tested (whether it be a generator or a motor) is placed in the position of machine No. 2 in Fig. 36. The field currents of machines No. 1 and No. 2 and the electromotive force of the booster are so adjusted that the armature current in the machine under test is full-load value, and the speed of the machine is the rated value. The machine under test should be operated as a motor or generator, depending upon its rating. The details of the heat run are discussed in § 61.

66. Regulation by Hutchinson's method. The machines do not need to be identical for this test. It is necessary that the dynamos (booster and running mate) be large enough to accommodate the machine to be tested.

If the dynamo to be tested is a motor, it is placed in the position of machine No. 2 in Fig. 36. The field currents of the two machines are so adjusted that each machine is acting as a motor and is not delivering any power; that is, $E_1 = E_2$. The field

current of the motor must be of such value that the motor will operate at rated speed at full load. (The booster electromotive force is made equal to zero.) The speed is noted for this set of conditions and it corresponds to the no-load speed of the motor.

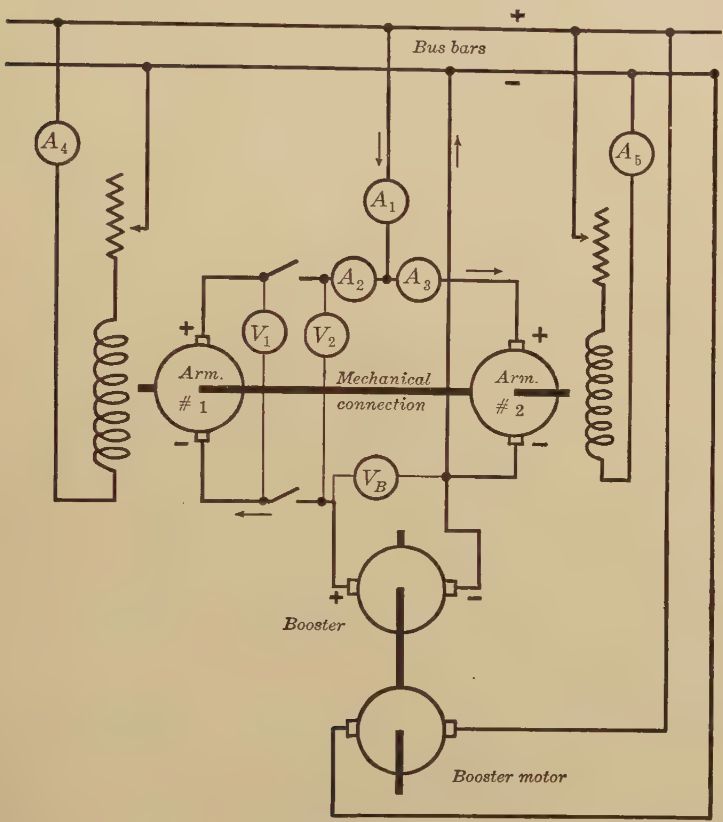

FIG. 36. Hutchinson's opposition method of testing two direct-current dynamos. (Simplified diagram)

Then increase the booster electromotive force in such direction that the machine under test is a motor and carrying full-load armature current. Note the new speed of the motor. The speed regulation can be determined by using the two speeds just noted. (See § 62.)

If the dynamo to be tested is a generator, it is placed in the position of machine No. 1 in Fig. 36. The wiring diagram must

be modified, so that the machine to be tested as a generator is self-excited. The full-load adjustment is made by properly adjusting the field currents of the three machines. The field current of the motor controls the speed of the motor as well as the generator and is adjusted to give the rated speed of the generator at full load. The field current of the generator is adjusted to give the rated difference of potential across the generator terminals at full load. The booster field is so adjusted that the generator to be tested is carrying full-load armature current. Then, maintaining the generator speed constant, adjust the booster field until the circulating current is reduced to zero. Note the generator difference of potential. The regulation of the generator can be determined by using the no-load and full-load differences of potential. (See § 62.)

67. Efficiency by Hutchinson's method. The machines must be identical for this test. It is necessary that the booster be large enough to accommodate the machine being tested.

If the machine to be tested is a generator, it must be placed in the position of dynamo No. 1 in Fig. 36 and operated as a generator. The field currents of the two machines must be kept the same in order that the induced electromotive forces will remain the same. If this is not done, the iron losses will differ for the two machines. The field currents of the two identical machines and the electromotive force of the booster are adjusted to keep the speed at the rated value and give the desired armature current.

Let I_1 = current being supplied from the bus bars,
and V = bus-bar difference of potential.

Then the losses in the generator are approximately equal to

$$\frac{VI_1 + V_bI_2}{2} \text{ watts. (See Fig. 36.)}$$

The efficiency of the generator is approximately equal to

$$\frac{V(I_2 - I_4)}{VI_2 + \frac{VI_1}{2} + \frac{V_bI_2}{2}}.$$

If the machine is to be tested as a motor, it must be placed in the position of dynamo No. 2 in Fig. 36, and operated as a motor. The electromotive forces of the two machines must be

kept the same. The field currents of the identical machines and the electromotive force of the booster are adjusted to give the rated full-load current at rated speed. For other values of load the booster electromotive force is changed to give the desired result and the field currents of the identical machines are kept constant. Then the losses in the motor are approximately equal to

$$\frac{VI_1 + V_bI_2}{2} \text{ watts. (See Fig. 36.)}$$

The efficiency of the motor is approximately equal to

$$\frac{VI_3 - \frac{VI_1}{2} - \frac{V_bI_2}{2}}{V(I_3 + I_5)}.$$

EXPERIMENT 6–D

Efficiency and Regulation of a Dynamo by Hutchinson's Opposition Method

Object. To determine the efficiency and regulation of a machine by Hutchinson's opposition method of testing.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XIV.

Apparatus. Two identical machines, direct-connected preferably. A booster of suitable capacity and a motor for driving the booster. The necessary starting boxes and field rheostats.

Method. Connect the apparatus as indicated in the simplified diagram Fig. 36. Start machine No. 2 as a motor. Adjust the field currents of the machines under test so that their induced electromotive forces are equal. If the dynamos are rated as generators, adjust the field currents of the two identical machines and the electromotive force of the booster so as to keep the speed at rated value, and obtain the desired armature current. If the dynamos are rated as motors, adjust the field currents of the two identical machines and the electromotive force of the booster so as to obtain rated speed at full-load armature current. Hold the shunt-field currents of the two identical machines constant throughout the test. Vary the circulating current by varying the field current of the booster. Take readings at various loads from zero to 125 per cent of rating.

Make the necessary changes in connections and determine the regulation of the machine.

Curves. Plot the efficiency and regulation curves.

68. Kapp's opposition method. This method requires no booster or auxiliary motor. It is the simplest method from the standpoint of necessary equipment. All losses are supplied

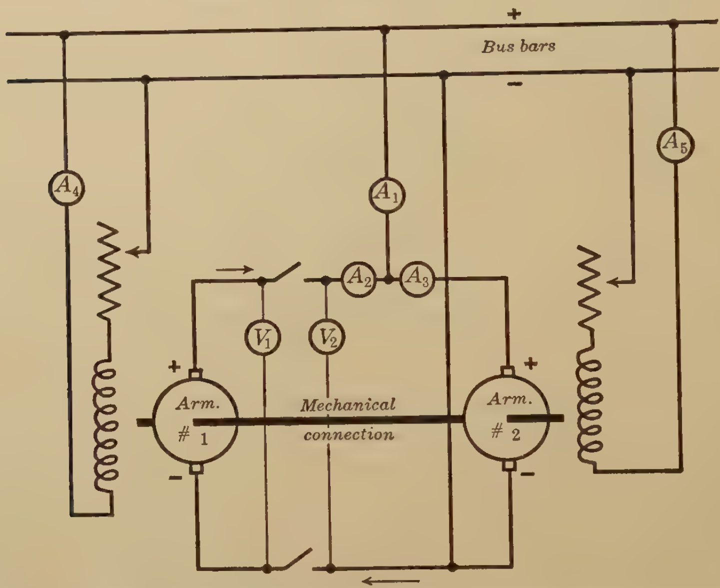

FIG. 37. Kapp's opposition method of testing two direct-current dynamos. (Simplified diagram)

electrically. The wiring diagram for Kapp's opposition method is shown in Fig. 37. The necessary starting box has been omitted to simplify the diagram.

Dynamo No. 2 is started as a motor. Dynamo No. 1 becomes a generator and its field is excited to such a value that $V_1 = V_2$. The switches shown can then be closed if the polarity is correct. The electromotive forces must oppose each other in the local circuit.

The bus-bar difference of potential must be equal to the rated difference of potential of the particular machine to be tested. All adjustments are made by varying the field currents of the two machines.

69. Temperature rise by Kapp's method. The machines do not need to be identical for this test. The running mate must be large enough to accommodate the machine to be tested. The dynamo to be tested should be operated as a generator or motor, depending upon its rating. The field currents are so adjusted that the machine under test is acting as a generator or motor, is operating at the proper speed, and is carrying the rated full-load armature current. The other details of the heat run have been discussed in § 61.

70. Regulation by Kapp's method. This method does not lend itself readily to the determination of the voltage regulation for a generator. The speed regulation of a motor can be determined. It is not necessary that the machines be identical in size for this test, but the running mate must be large enough to accommodate the motor being tested. The field currents are adjusted so that the machine under test is operating as a motor, at rated speed and full-load armature current. Then the generator field is varied until both machines are acting as motors and each machine is receiving just enough power to supply its own losses. The speed is noted and this corresponds to the no-load speed. It is assumed that the bus-bar difference of potential is equal to the voltage rating of the motor under test, and remains constant during the test. The speed regulation can be determined as explained in § 62.

71. Efficiency by Kapp's method. Kapp's opposition method gives only approximate results for efficiency when identical machines are used. In order to load the machines it is necessary to vary the field currents and therefore the division of iron losses changes for every load. The machine acting as a generator will have the greater iron loss.

However, the armature of the machine which acts as a generator carries slightly less current than the motor armature, and therefore the armature copper loss of the motor will be greater than that of the generator. One half of the electrical power supplied from the bus bars to the armatures of the identical machines plus the field loss of the particular machine being tested is very nearly equal to the total losses of that dynamo. The machine to be tested should be operated as a generator or motor, depending on its rating.

EXPERIMENT 6-E

The Efficiency of a Dynamo by Kapp's Opposition Method

Object. To determine the efficiency of a dynamo by Kapp's opposition method of testing.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XIV.

Apparatus. Two identical machines, direct-connected preferably. Suitable starting box and field rheostats.

Method. Connect the apparatus as indicated in the simplified diagram Fig. 37. If the machines are rated as generators, adjust the field current of machine No. 2 so as to hold the speed constant at rated value. Adjust the field current of machine No. 1 so as to obtain the desired circulating current. If the machines are rated as motors, adjust the field current of machine No. 2 so as to obtain rated speed at full load and maintain this field current constant throughout the test. Adjust the field of machine No. 1 so as to obtain the desired circulating current. Take readings at various loads from zero to 125 per cent of rating. If the machines are rated as motors determine the speed regulation.

Curves. Plot the efficiency curve of the machine. If the machines are rated as motors, also plot the regulation curve.

EXPERIMENT 6-F

Temperature Rise by Kapp's Opposition Method

Object. To determine the temperature rise by Kapp's opposition method of testing.

Reference. A.I.E.E. Standards, No. 5 (July, 1925).

Apparatus. Same as in Experiment 6-E, except that the machines need not be identical.

Method. Measure the resistances of the armature, exclusive of brush-contact drop, and the resistance of the shunt field, before the test is started. Note the temperature of the machine at the time the resistances are measured. Place thermometers on the various stationary parts of the machine. Use two thermometers for reading room temperature. Load the machine under test to full load and maintain the load constant. Take readings every fifteen minutes until steady temperature has

been reached. Stop the machine and immediately apply thermometers to the armature and commutator. Read all thermometers every half minute until the maximum readings have been reached. As soon as the machine stops measure the resistances of the armature and the shunt field.

Curves. Plot the various temperature readings as ordinates and time as abscissas.

Questions. 1. Why does the apparent temperature of the machine continue to rise after the machine has been stopped?

2. How does the temperature calculated from resistance measurements compare with the observed temperature of the armature?

3. What are the maximum allowable temperatures for various insulating materials?

72. Separation of losses by the retardation method. Retardation curves may be used for separating the losses of a dynamo. A retardation curve can be obtained by bringing the dynamo armature to a relatively high speed as a motor, and shutting off the power being supplied to the armature. Speed readings must be taken at regular intervals of time. A curve is plotted between time as abscissas and speed as ordinates. Many such curves can be plotted, as may be noted by referring to Fig. 38.

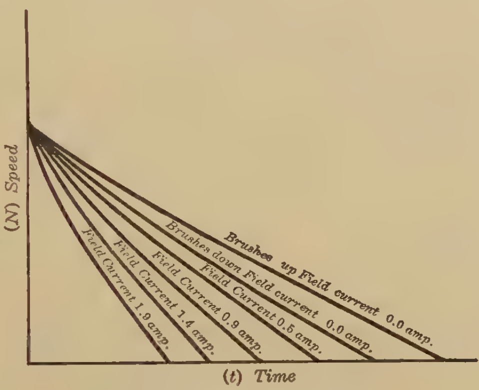

FIG. 38. Retardation curves

The theory of the retardation method is as follows. The kinetic energy stored in the rotating part of the dynamo is equal to $\frac{1.3564}{2} K\omega^2$ watt-seconds,

where $K = \Sigma\left(\frac{W}{g} r^2\right)$ = moment of inertia in mass-foot^2 units,

W = weight, in pounds, of a particle of the rotating part,
g = gravitational constant = 32.2,
r = distance from axis to the particle expressed in feet,
and ω = angular velocity in radians per second.

If the factor 1.3564 is omitted in the above expression, the energy is expressed in foot-pounds.

The kinetic energy that is stored in the rotating part is equal to $\frac{1}{2}\,CN^2$ watt-seconds, where

C = a constant that can be determined for a particular machine if necessary, and
N = revolutions per minute.

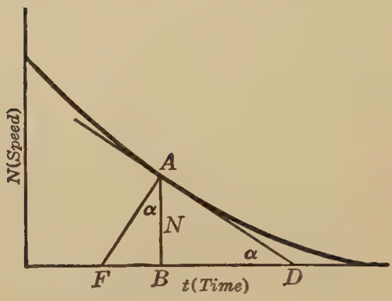

FIG. 39. Retardation curve analysis

At any particular time when the dynamo is slowing down in the above-mentioned test the kinetic energy of the machine is being absorbed to overcome the losses of the machine. In other words,

$$\frac{d(\frac{1}{2}CN^2)}{dt} = p_s,$$

where p_s = power consumed to overcome losses.

Therefore $$p_s = CN\frac{dN}{dt} \text{ watts.}$$

This power may be readily determined from a retardation curve. (See Fig. 39.) The line AD is straight and is tangent to the retardation curve at the point A. $\frac{dN}{dt} = -\tan\alpha$. The line AF is drawn perpendicular to the tangent at the point A. The power loss is equal to $+\,CN\frac{dN}{dt}\cdot$ Therefore the power loss is proportional to $CN\frac{FB}{AB} = C\,(FB)$. In other words, the power loss is proportional to the subnormal FB.

It is only necessary to determine the amount of power represented by a particular length subnormal FB. This can be easily determined for the retardation curves. The dynamo,

being driven as a motor, can be held at one speed. Note the power input to the armature. The armature ($I_a^2 r_a$) and brush-contact ($2\ I_a$) losses can be subtracted; the remainder will be

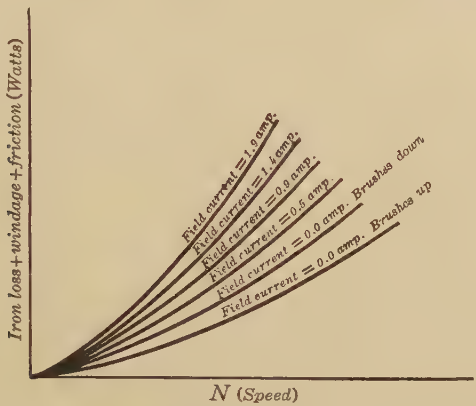

FIG. 40. No-load losses derived from retardation curves

iron and friction losses. Construct the subnormal corresponding to the speed at which the power input was observed (use the correct retardation curve). The power absorbed by windage, friction, and iron losses is represented by this subnormal. Now

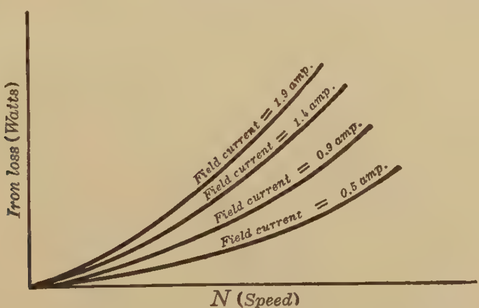

FIG. 41. Iron losses derived from curves in Fig. 40

that the power represented by a certain length subnormal is known, the curves represented in Fig. 38 can be used to develop the curves shown in Fig. 40.

Then the curves similar to those shown in Fig. 41 may be plotted.

The power consumed to overcome losses (p_s) may be readily determined from the retardation curves in another way if the moment of inertia of the rotating part is known.

Let K = moment of inertia of the rotating part in mass-foot^2 units.

Then, with the armature rotating,

$$\text{stored kinetic energy} = \frac{1.3564}{2} K\omega^2 \text{ watt-seconds,}$$

but

$$\omega = \frac{2\,\pi N}{60}.$$

Therefore stored kinetic energy

$$= 0.007437\, KN^2 \text{ watt-seconds.}$$

Then

$$p_s = \frac{d\,(0.007437\, KN^2)}{dt} = 0.014874\, KN \frac{dN}{dt} \text{ watts.}$$

With this equation p_s can be determined from a retardation curve for a given speed if K is known.

K, the moment of inertia, may be determined as follows:

The kinetic energy stored in the rotating part of a dynamo equals $\frac{K\omega^2}{2}$ foot-pounds. Then

$$\frac{d\,(\text{energy stored})}{dt} = K\omega \frac{d\omega}{dt} \text{ foot-pounds per second,}$$

but

$$K\omega \frac{d\omega}{dt} = \frac{2\,\pi TN}{60},$$

where T = retarding torque exerted, due to losses, in pound feet.

Therefore

$$TK = K \frac{d\omega}{dt} \text{ pound feet.}$$

In order to determine K a known retarding torque must be applied. A Prony brake may be used. Let

$$T' = \text{applied retarding torque}$$

$$= K\left(\frac{d\omega_1}{dt} - \frac{d\omega}{dt}\right),$$

at the same speed, where $d\omega_1$ is taken from a retardation curve with the known retarding torque, and $d\omega$ is taken from a retardation curve without any external retarding torque.

Then

$$K = \frac{T'}{\dfrac{d\omega_1}{dt} - \dfrac{d\omega}{dt}},$$

but $$\omega = \frac{2\,\pi N}{60} \quad \text{and} \quad \frac{d\omega}{dt} = \frac{2\,\pi}{60}\frac{dN}{dt}.$$

Therefore $$K = \frac{60}{2\,\pi} \times \frac{T'}{\frac{dN'}{dt} - \frac{dN}{dt}} \text{ mass-foot}^2 \text{ units,}$$

where $\frac{dN'}{dt}$ is taken from a retardation curve with the known retarding torque, and $\frac{dN}{dt}$ is taken from a retardation curve without any external retarding torque. $\left(\frac{dN'}{dt}\right.$ and $\frac{dN}{dt}$ must be taken for the same instantaneous speeds.$\left.\right)$

This method works very well for machines that have a large moment of inertia. If the machine under test does not have a large moment of inertia, a flywheel whose moment of inertia is known may be mounted upon the shaft. The moment of inertia of the combined system may be determined and then the moment of inertia of the machine alone may be computed.

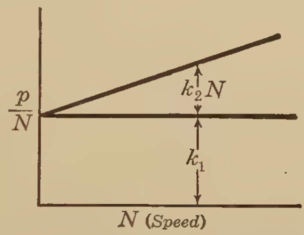

FIG. 42. Curve used to separate the iron loss of a dynamo into its component parts; namely, eddy-current and hysteresis losses

Separation of eddy-current and hysteresis losses are found as follows: After curves similar to those shown in Fig. 41 are plotted, the total iron loss may be separated into its component parts; namely, the eddy-current and hysteresis losses.

Let $p =$ total iron loss,
$k_1 =$ a constant,
and $k_2 =$ a constant.
Then $p = k_1N + k_2N^2$,
where $k_1N =$ hysteresis loss in watts,
and $k_2N^2 =$ eddy-current loss in watts.

Then $\frac{p}{N} = k_1 + k_2N$. Plot a new curve with $\frac{p}{N}$ as ordinates and N as abscissas, for any particular curve as shown in Fig. 41. (See Fig. 42.) The slope of the curve will be equal to k_2. The value of k_1 can be taken directly from the curve. The hysteresis

loss may be determined by multiplying k_1 by N. The eddy-current loss may be determined by multiplying the proper value of k_2N by N.

EXPERIMENT 6-G

Efficiency and Separation of Losses by the Retardation Method

Object. To separate the various losses and determine the efficiency of a dynamo by the retardation method.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XIII.

Apparatus. A dynamo (motor or generator) having a reasonably large moment of inertia. A suitable starting box and field rheostat.

Method. Connect the machine to a suitable source of potential difference and operate it as a motor. Allow the machine to run for several minutes before starting the test so that the oil will be properly distributed through the bearings. Increase the speed to the highest safe value and take readings of terminal difference of potential, armature current, shunt-field current, and speed. Open the armature circuit and while the machine is slowing down take readings of instantaneous speed at regular intervals of time until the machine stops. Repeat the above, using several different values of field current, but always starting with the same initial speed. Obtain the retardation-speed curve for zero field current. Arrange some means whereby the brushes can be lifted from the commutator as soon as the armature and field circuits have been opened. Obtain the retardation-speed curve for the machine with zero field current and with the brushes lifted.

Precautions. Take the necessary precautions in opening the field circuit, so as not to damage the insulation.

Curves. Plot the necessary curves to illustrate your results.

Questions. 1. In the machine tested, how do the hysteresis and eddy-current losses compare?

2. How does the accuracy of this method compare with the accuracy of the method used in Experiment 6-A?

3. Would the accuracy of the method be increased by placing a flywheel on the armature shaft so as to increase its moment of inertia?

CHAPTER VII

ALTERNATING-CURRENT CIRCUITS

73. Introduction. Circuits which contain lumped resistance, lumped self-inductance, and lumped capacitance are considered in this chapter. It is assumed in all cases that steady conditions have been reached. (The transitory parts of the current equations are assumed to be equal to zero.) Sine waves of difference of potential and current are considered.

74. Resistance and constant-permeability self-inductance in series. The current in a circuit containing resistance and self-inductance in series lags behind the overall difference of potential impressed. Let

$i = I_m \sin (2\,\pi f t)$, where
$i =$ instantaneous value of current in the circuit,
$I_m =$ maximum value of current in the circuit,
$f =$ frequency of current in cycles per second, and
$t =$ instantaneous time considered.

Then

$v = I_m Z \sin\left(2\,\pi f t + \tan^{-1}\dfrac{X_L}{R'}\right)$, where
$v =$ instantaneous value of overall difference of potential impressed,
$Z =$ impedance of the circuit in ohms $= \sqrt{(R')^2 + (X_L)^2}$,
$I_m Z =$ maximum overall difference of potential,
$X_L = 2\,\pi f L =$ reactance of the circuit in ohms,
$L =$ coefficient of self-induction of the circuit in henrys, and
$R' =$ a-c. resistance of the circuit in ohms. (This must include skin effect and the effect of eddy-current losses at the proper frequency.)

This may be represented vectorially as follows: (See Fig. 43.)

I (effective value of current) $= \dfrac{I_m}{\sqrt{2}}$,

and V (effective value of difference of potential) $= \dfrac{V_m}{\sqrt{2}}$.

Therefore the above vector diagram may be redrawn. (See Fig. 44.)

It is evident that $I = \frac{V}{Z} = \frac{V}{\sqrt{(R')^2 + (X_L)^2}}$. The IR' vector represents that component of the overall difference of potential which overcomes the IR' drop in the circuit. The IX_L vector

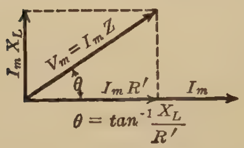

FIG. 43. Vector diagram of a series circuit containing resistance and inductance

The vectors represent maximum values

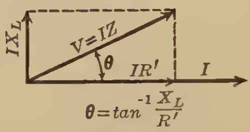

FIG. 44. Vector diagram of a series circuit containing resistance and inductance

The vectors represent effective values

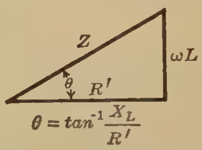

FIG. 45. Impedance polygon for a series circuit containing resistance and inductance

represents that component of the overall difference of potential which balances the electromotive force induced in the circuit due to magnetic flux changes. The V vector represents the total applied difference of potential.

If the numeric values of the above difference-of-potential vectors are divided by I and the results plotted as shown in Fig. 45, the result is called the impedance polygon of the circuit.

The power factor of the above circuit is the cosine of the angle between V and I, or $\cos \tan^{-1} \frac{X_L}{R'}$. The power factor also equals $\frac{R'}{Z}$.

It may be readily shown that for a toroidal solenoid with a constant-permeability magnetic circuit

$$L = \frac{4\,\pi N^2 A\mu}{10^9 l} \text{ henrys, where}$$

N = number of turns of wire on coil,
A = area of cross section of magnetic circuit in sq. cm.,
μ = permeability of magnetic material, and
l = length of magnetic circuit in centimeters.

The above formula for L holds very nearly for a long straight solenoid. (The length of the solenoid must be equal to or greater

than ten times its diameter.) For *short* solenoids the above formula will not give the desired results.*

In the above formulas R' must be adjusted to take care of skin effect and any eddy-current losses in the conductors. If an air-core inductance is used, R' is equal to the total power input to the circuit divided by I^2. A wattmeter properly connected will read the total power input to the circuit.

EXPERIMENT 7-A

Inductive Reactance and Resistance in Series

Object. To study a circuit containing lumped self-inductance and resistance in series. To study the effect of the number of turns on the self-inductance of a coil.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. VI.

Apparatus. An air-core inductance coil, preferably one having low ohmic resistance. A noninductive resistance. The necessary instruments. A source of variable frequency power supply.

Method. Connect the apparatus and instruments as shown in Fig. 46. Adjust the inductance of the coil or the resistance of the circuit so that the inductive reactance will be approximately equal to the resistance of the circuit at the middle of the available frequency range. Vary the frequency from the lowest obtainable to the highest which can be secured without excessive alternator speed, and maintaining I constant, take readings of V_t, V_r, V_L, I, and P_L, at each increment of frequency. From these readings calculate the resistance of the inductance coil, the resistance of the resistor, the inductive reactance, and the coefficient of self-inductance of the coil. Draw a typical impedance polygon illustrating the results. Increase or decrease

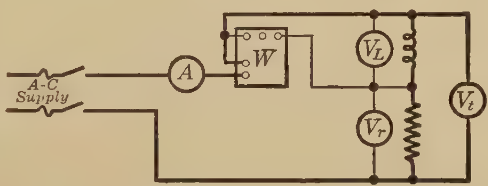

FIG. 46. Resistance and inductance in series

* University of Illinois Engineering Experiment Station, *Bulletin No. 53*, "Inductance of Coils," by Morgan Brooks and H. M. Turner.

the number of turns on the coil and repeat the above experiment. Calculate and illustrate as above. From physical dimensions calculate the inductance of the coil.

Curves. Plot the necessary curves to illustrate your results.

Questions. 1. How does the self-inductance of the coil vary with frequency?

2. With the number of turns?

3. How does the inductive reactance vary with the number of turns?

4. With the frequency?

5. What might cause the effective resistance of the coil to differ from the resistance measured by the drop-of-potential method using direct current?

75. Iron-core coil. The permeability of iron is a function of the flux density, and therefore the instantaneous coefficient of self-induction is a function of the instantaneous current in the coil. This complicates the solution of the problem greatly. When a sine wave of difference of potential is impressed across a circuit containing an iron-core coil, the resultant current wave will not be a sine wave. The current wave will contain a fundamental wave, a prominent third harmonic wave, a somewhat smaller fifth harmonic wave, etc.

A circuit consisting of an iron-core coil is sometimes handled as follows: A wattmeter is properly connected to indicate the total power input to the circuit. An ammeter is inserted into the circuit so that the current can be noted. A voltmeter is used to determine the difference of potential impressed. The wattmeter reading indicates the actual I^2R' loss plus the eddy-current and hysteresis losses in the iron. The quantity R' is the a-c. resistance of the wire and it is greater than the d-c. ohmic resistance in order to take care of skin effect and conductor eddy-current losses. The wattmeter reading, divided by the current squared, gives the effective resistance of the circuit. The impedance of the circuit equals $\frac{V}{I}$ ohms. The effective reactance, X (effective), of the circuit equals $\sqrt{Z^2 - (R, \text{effective})^2}$ ohms. The effective coefficient of self-induction equals $\frac{X \text{ (effective)}}{2\,\pi f}$ henrys.

Fig. 47 is a vector diagram for a circuit consisting of an iron-core coil. It will be noted that R (effective) is larger than R', and X (effective) is smaller than the true reactance.

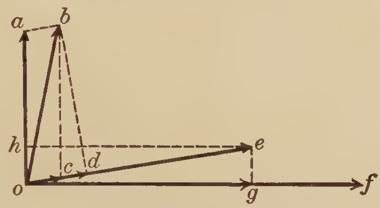

FIG. 47. Vector diagram for a coil having an iron core

oe = total equivalent sine wave of current,
og = magnetizing component of total current,
oh = power component of total current,
of = flux in iron core,
oa = component of applied difference of potential to balance the electromotive force generated by the changing of magnetic flux,
oc = component of the applied difference of potential to overcome the IR' drop,
ob = total difference of potential impressed,
od = component of applied difference of potential to overcome the IR (effective) drop,
db = component of applied difference of potential to overcome the IX (effective) drop,

$$X \text{ (effective)} = \frac{db}{oe},$$

$$X \text{ (actual)} = \frac{oa}{og},$$

$$X \text{ (actual)} > X \text{ (effective)},$$

$$R \text{ (effective)} = \frac{od}{oe},$$

$$R' = \frac{oc}{oe},$$

and
$$R \text{ (effective)} > R'.$$

For a given iron-core coil R (effective) and X (effective) vary with the effective value of the current in the coil. As the current approaches zero, R (effective) approaches R'. As the current is increased, R (effective) increases to a maximum and then decreases and approaches R'. The reactance X (effective) approaches a comparatively low value as the effective value of the current approaches zero. As the current is increased, X (effective) increases to a maximum and then decreases.

EXPERIMENT 7-B

An Inductance Coil having an Iron Core

Object. To study the properties of an inductance coil having an iron core.

Reference. Lawrence, "Principles of Alternating Currents," Chap. VII. McGraw-Hill Book Company, Inc.

Apparatus. An inductance coil having an iron core. A transformer is suitable for this purpose.

Method. Connect the coil, in series with a rheostat for controlling the current, to a suitable source of power supply. Connect a voltmeter so as to measure the effective value of the difference of potential across the coil, and an ammeter to measure the effective value of the current flowing in the coil. Also connect a wattmeter to measure the power supplied to the coil. Vary the current flowing through the coil by steps and take readings of V, I, and P, for each step. Calculate the effective resistance and the effective reactance of the coil and draw a typical impedance polygon illustrating the results. Using direct current measure the ohmic resistance of the coil. Calculate the actual reactance and the actual coefficient of self-induction of the coil, assuming that there are no additional losses due to skin effect or eddy currents in the conductor. Plot a vector diagram illustrating the results.

Curves. Plot the curves necessary to illustrate your results.

Question. Why does the coefficient of self-inductance vary with changes in current?

76. Resistance and capacitance in series. The current in a circuit containing resistance and capacitance in series leads the total difference of potential impressed.

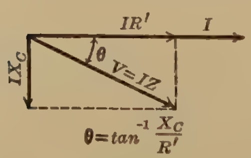

FIG. 48. Vector diagram of a series circuit containing resistance and capacitance

The vectors represent effective values

Let $i = I_m \sin (2\,\pi f t)$.

Then

$$v = I_m Z \sin \left(2\,\pi f t - \tan^{-1} \frac{X_c}{R'}\right),$$

where

$$Z = \sqrt{(R')^2 + (X_c)^2} \text{ ohms},$$

$$X_c = \frac{1}{2\,\pi f C} = \text{reactance in ohms},$$

and C = capacitance of the series circuit in farads.

The above equations may be represented vectorially as shown in Fig. 48. It is evident that

$$I = \frac{V}{Z} = \frac{V}{\sqrt{(R')^2+(X_c)^2}} \text{ amperes.}$$

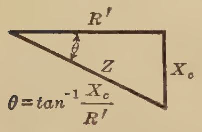

FIG. 49. Impedance polygon of a series circuit containing resistance and capacitance

The corresponding impedance polygon is shown in Fig. 49.

The power factor of the above circuit is the cosine of the angle between V and I. The power factor is also equal to

$$\frac{R'}{Z}, \text{ or } \cos\tan^{-1}\frac{X_c}{R'}.$$

EXPERIMENT 7-C

Resistance and Capacitance in Series

Object. To study conditions in a circuit containing lumped capacitance and resistance in series.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. II, Exp. 2.

Apparatus. A condenser (preferably variable). A resistor. A source of variable frequency power supply.

Method. Connect the apparatus and instruments as shown in Fig. 50. If the condenser is a variable condenser, take a set of readings maintaining terminal difference of potential and frequency constant, and varying the capacitance of the condenser by steps. At each step take readings of V_t, V_c, V_r, I, and P_c. Take a similar set of readings leaving the capacity of the condenser fixed, maintaining terminal difference of potential constant, and varying the resistance of the circuit. Take a similar set of readings varying the frequency of the supply difference of potential, maintaining capacitance, resistance, and current constant. Draw a typical impedance polygon.

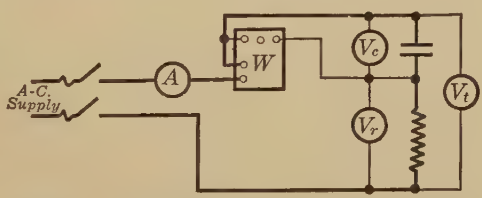

FIG. 50. Resistance and capacitance in series

Curves. Plot the necessary curves to illustrate your results. Always use the independent variable as abscissas.

Questions. 1. How does the capacity reactance of the condenser vary with frequency?

2. How does the capacitance of the condenser vary with frequency?

3. With current?

4. What losses occur in a condenser?

5. How can such losses be reduced?

77. Resistance, constant-permeability self-inductance, and capacitance in series. The current in a circuit containing resistance, constant-permeability self-inductance, and capacitance in series may lead or lag behind the difference of potential impressed.

Let $$i = I_m \sin (2\,\pi f t).$$

Then $$v = I_m Z \sin\left(2\,\pi f t + \tan^{-1} \frac{X_L - X_c}{R'}\right),$$

where $$Z = \sqrt{(R')^2 + (X_L - X_c)^2} \text{ ohms.}$$

Fig. 51 is a vector diagram for the above circuit. The current is lagging behind the difference of potential impressed because X_L is greater than X_c. The power factor is equal to

$$\cos \tan^{-1} \frac{(X_L - X_c)}{R'}.$$

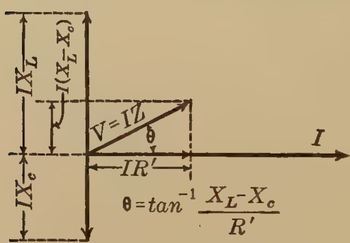

FIG. 51. Vector diagram of a series circuit containing resistance, inductance, and capacitance

It is evident that

$$I = \frac{V}{\sqrt{(R')^2 + (X_L - X_c)^2}}$$

amperes.

If the circuit contains several parts composed of resistances, inductances, and condensers, it will be necessary to handle the problem as follows: $Z_t = \sqrt{(\Sigma R')^2 + (\Sigma X_L - \Sigma X_c)^2}$ and $I = \frac{V}{Z_t}$, where Z_t equals the total impedance of the circuit.

Series circuits may be handled by the use of complex expressions. In the equations below the letters with bars over them indicate the complex expressions for the terms considered. The

complex expression for the impedance of a series circuit is equal to

$$\overline{Z}_t = \Sigma R' + j(\Sigma X_L - \Sigma X_c). \text{ Then } \overline{I} = \frac{\overline{V}}{\overline{Z}_t}, \text{ or } \overline{V} = \overline{I}\overline{Z}_t.$$

A series circuit containing several condensers and coils will be in resonance when the summation of the X_L's equals the summation of the X_c's. When this condition exists, $Z = \Sigma R'$, and the angle between I and V (total) is zero. The power factor of the circuit is equal to one.

EXPERIMENT 7-D

Series Resonance

Object. To study the phenomenon of resonance as it occurs in a series circuit containing inductance and capacitance.

Apparatus. An inductance, preferably variable. A condenser. A rheostat. A source of variable frequency power supply.

Reference. Lawrence, "Principles of Alternating Currents," Chap. VII.

Method. Series resonance can be produced by varying any one of the three factors, inductance, capacitance, or frequency, until the necessary relations are established in the circuit. It is therefore possible to take three different sets of readings to illustrate this phenomenon: first, inductance can be varied, capacitance and frequency being maintained constant; second, capacitance may be varied, inductance and frequency being maintained constant; third, frequency may be varied, inductance and capacitance being maintained constant. Before taking a set of readings, the necessary adjustments should be made so that resonance will occur at about the middle of the available range of the independent variable. In each of these methods it is possible to maintain either constant difference of potential or constant current. If the terminal difference of potential is maintained constant, the current will be maximum at the point of resonance, being limited only by the resistance of the circuit. If the current is maintained constant, the terminal difference of potential will be minimum at resonance.

Precautions. Since at resonance the current is limited only by the resistance of the circuit, it is necessary to have a sufficiently high resistance or a sufficiently small supply difference of poten-

tial so that the current will not be excessive at resonance. Do not allow the difference of potential across the condenser or the inductance to exceed safe values.

Curves. Plot the curves necessary to illustrate the results of the experiment, using the independent variable as abscissas. These curve sheets should include curves of X_L, X_c, R', Z, and the differences of potential across the various parts as ordinates.

Questions. 1. What determines the point of resonance?

2. What is the relation between X_L and X_c at resonance?

3. What is the relation between V_L and V_c at resonance?

4. What would be the result of reducing the resistance of the circuit?

78. Parallel circuits. When circuits containing resistance, self-inductance, and capacitance are connected in parallel and a difference of potential is placed across the combination, the resultant total current is the vector sum of the individual currents. If the constants of such a combination as well as the difference of potential are known, the resultant current may be found as follows: (Assume a circuit as shown in Fig. 52.)

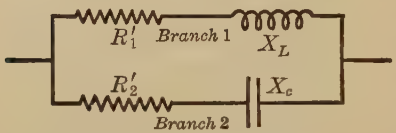

FIG. 52. Parallel circuit

$$\bar{Z}_1 \text{ (Branch 1)} = R_1' + jX_L.$$

$$\bar{Y}_1 \text{ (Branch 1)} = \frac{1}{\bar{Z}_1} = \frac{1}{R_1' + jX_L} \times \frac{R_1' - jX_L}{R_1' - jX_L} = \frac{R_1'}{Z_1^2} - j\frac{X_L}{Z_1^2}.$$

The term $\frac{R_1'}{Z_1^2}$ is called the conductance of Branch 1 and is represented by the letter g_1. The term $\frac{X_L}{Z_1^2}$ is called the susceptance of Branch 1 and is represented by the letter b_1. Therefore $\bar{Y}_1$ equals $g_1 - jb_1$. The quantity Y_1 is called the admittance of Branch 1.

$$\bar{Z}_2 = R_2' - jX_c.$$

$$\bar{Y}_2 = \frac{1}{\bar{Z}_2} = \frac{R_2'}{Z_2^2} + j\frac{X_c}{Z_2^2} = g_2 + jb_2.$$

In parallel circuits the complex expressions for admittance should be added to determine the total admittance.

$$\bar{Y}_t = g_1 + g_2 - j(b_1 - b_2).$$

$$\bar{I}_t = \overline{VY}_t, \text{ or } \bar{V} = \frac{\bar{I}_t}{\bar{Y}_t}.$$

$$\bar{I}_1 = \overline{VY}_1, \text{ or } \frac{\bar{V}}{\bar{Z}_1}.$$

$$\bar{I}_2 = \overline{VY}_2, \text{ or } \frac{\bar{V}}{\bar{Z}_2}.$$

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_t.$$

I_t = the square root of the sum of the squares of the horizontal and vertical components of $\bar{I}_t$. Here I_1 = the square root of the sum of the squares of the horizontal and vertical components of $\bar{I}_1$, and I_2 = the square root of the sum of the squares of the horizontal and vertical components of $\bar{I}_2$.

The power factor of Branch $1 = \frac{g_1}{Y_1} = \frac{R'}{Z_1}$. The power factor of Branch $2 = \frac{g_2}{Y_2} = \frac{R_2'}{Z_2}$. The power factor of the parallel combination is equal to $\frac{g_1 + g_2}{Y_t}$.

If the algebraic sum of the susceptances of any parallel combination is equal to zero the condition is known as parallel resonance. In the circuit above parallel resonance exists when $b_1 = b_2$. For parallel resonance I_t is in phase with V. The power factor of the combination is unity. The total current is a minimum.

EXPERIMENT 7–E

Parallel Resonance

Object. To study the phenomenon of resonance as it occurs in a parallel circuit containing inductance and capacitance.

Reference. Lawrence, "Principles of Alternating Currents," Chap. VII.

Apparatus. Same as in Experiment 7-D.

Method. Parallel resonance can be produced by varying any one of the three factors, inductance, capacitance, or frequency, until the necessary relations are established in the circuit. It is,

therefore, possible to take three different sets of readings to illustrate this phenomenon, as has been explained in Experiment 7-D. In addition to the above, insert some resistance in series with either the inductance or the capacitance and notice the effect of this resistance upon the point of resonance.

Curves. Plot the curves necessary to illustrate the results of the experiment, always using the independent variable as abscissas.

Questions. 1. What determines the point of resonance?

2. What is the relation between X_L and X_c at resonance?

3. What is the relation between b_L and b_c at resonance?

4. What is the effect of adding resistance in series with the inductance of the circuit?

5. In series with the capacitance?

CHAPTER VIII

TRANSFORMERS

79. Fundamental principles. A transformer is a magnetic circuit interlinked with two or more electrical circuits.

A low-reluctance magnetic circuit is desirable for a transformer. This is obtained by making a closed high-permeability iron path. The magnetic circuit is laminated to reduce eddy-current losses.

The electrical winding which is connected to the power supply is called the *primary* of the transformer. The electrical winding to which the load is attached is called the *secondary* of the transformer.

The mutual flux of the magnetic circuit threads every winding turn that is on the transformer. When the mutual flux changes the rate of change of flux is the same for every turn, and therefore the electromotive force induced per turn is the same for all windings of the transformer. The electromotive forces induced in the turns are 90 degrees behind the mutual flux.

Let N_1 = number of primary turns,
N_2 = number of secondary turns,
Φ = mutual flux,
E_1 = induced electromotive force (effective value) in primary due to changing of mutual flux,
E_2 = induced electromotive force (effective value) in secondary due to changing of mutual flux,
V_1 = difference of potential impressed across the primary terminals,
V_2 = difference of potential across the secondary terminals,
r_1 = primary a-c. resistance,
r_2 = secondary a-c. resistance,
x_1 = primary leakage reactance due to primary leakage flux,
x_2 = secondary leakage reactance due to secondary leakage flux,

z_1 = primary impedance = $\sqrt{r_1^2 + x_1^2}$,
z_2 = secondary impedance = $\sqrt{r_2^2 + x_2^2}$,
I_0 = exciting current,
I_M = magnetizing component of the exciting current,
I_c = core-loss component of the exciting current,
I' = load component of primary current,
I_1 = total primary current,
and I_2 = secondary current.

Then
$$\frac{E_1}{E_2} = \frac{N_1}{N_2}.$$

The mutual flux of the transformer is produced by I_M, the magnetizing component of the exciting current. The exciting current I_0 is produced when a difference of potential V_1 is impressed across the primary terminals. Hence V_1 must be great enough, first, to balance the electromotive force induced in the primary due to the alternating of the mutual flux, secondly, to overcome the I_1r_1 drop of the primary, and thirdly, to overcome the I_1x_1 drop (the electromotive force which is induced in the primary by the alternating of primary leakage flux). When the secondary current is zero the exciting current will be the total primary current.

A secondary current which may be produced by attaching a load to the secondary terminals will produce a magnetomotive force proportional to N_2I_2. This disturbs the magnetic relations of the transformer so that a load component of primary current is drawn. This load component of the primary current produces a magnetomotive force that just balances the magnetomotive force of the secondary. In other words

$$N_1I' = N_2I_2,$$

or
$$I' = \left(\frac{N_2}{N_1}\right)I_2.$$

80. Vector diagram. The complete vector diagram for a transformer with an inductive load is shown in Fig. 53. In this diagram $\frac{N_1}{N_2} = 2$, and consequently $\frac{E_1}{E_2} = 2$, and $\frac{I_2}{I'} = 2$. The load power-factor angle is θ_2. The transformer-input power-factor angle is θ_1. The voltage-drop vectors and I_0 are drawn relatively large in order to clarify the diagram.

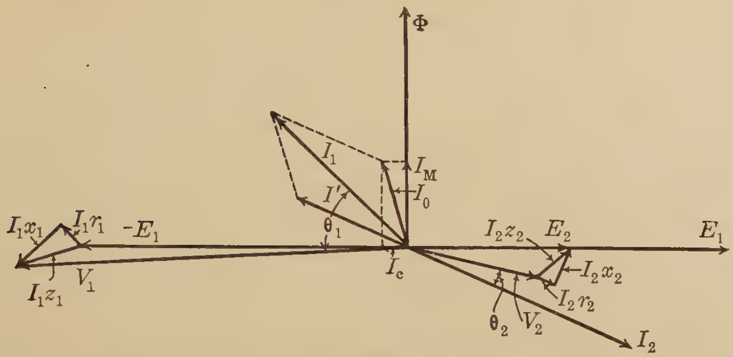

FIG. 53. Complete vector diagram of a transformer with inductive load

81. Winding connections. There is frequently more than one winding for the transformer primary. These windings should be connected so that their magnetomotive forces will add when the exciting current flows. When the transformer has two identical windings on the primary and they are connected so that their magnetomotive forces are not additive, an excessive current will flow if the normal difference of potential is impressed on the primary. Since no mutual flux is produced the current is limited only by the small impedance of the primary.

There is usually more than one winding for the transformer secondary. To obtain the maximum difference of potential for the load the secondary windings should be connected so that the electromotive forces are additive. If the transformer has two identical windings on the secondary, they may be connected in series or in parallel. When connected in series their electromotive forces may either add or subtract. If the electromotive forces are additive, the total difference of potential will be twice the difference of potential of one coil and the line current will be the winding current. If the electromotive forces are in opposition, the total difference of potential will be zero. In the parallel connection with the electromotive forces acting in the same direction, the terminal difference of potential will be the difference of potential of either winding and the line current will be twice the current per winding. If the coils are connected in parallel, and the electromotive forces act in opposite directions, the secondary is short-circuited, and an enormous current will flow in the windings.

EXPERIMENT 8-A

Connections of a Four-Coil Transformer

Object. To study the various possible connections of a transformer having two primary coils and two secondary coils.

Reference. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. II, Exp. 27.

Apparatus. A transformer having two primary coils and two secondary coils preferably of the ordinary distribution type. Voltmeters of suitable range.

Method. Use the high-tension side of the transformer as the primary and place a small fuse in series with this winding. (The size of the fuse will depend upon the size of the transformer.) Connect the coils of the transformer in the following ways and observe what takes place in each case. Also measure the terminal difference of potential of both primary and secondary in each case.

Connections:

Primaries — series cumulative, secondaries — series cumulative.
Primaries — series cumulative, secondaries — parallel cumulative.
Primaries — series cumulative, secondaries — series differential.
Primaries — series cumulative, secondaries — parallel differential.
Primaries — parallel cumulative, secondaries — series cumulative.
Primaries — parallel cumulative, secondaries — series differential.
Primaries — parallel cumulative, secondaries — parallel cumulative.
Primaries — parallel cumulative, secondaries — parallel differential.
Primaries — series differential, secondaries — series cumulative.
Primaries — parallel differential, secondaries — series cumulative.

In each case give the reasons for the results obtained. Show by diagram each of the connections used and label each diagram with the voltmeter readings obtained. Mark plainly the cases where the fuses were blown.

Questions. 1. Where should the fuses intended to protect the transformer be placed — in the primary or secondary circuit? Explain.

2. Devise a test for identifying transformer terminals, using fuses and a suitable source of power.

3. Also a test for identifying transformer terminals, using a primary cell and a galvanometer-type voltmeter.

EXPERIMENT 8-B

The Transformation Ratio of a Transformer

Object. To determine experimentally the ratio of the number of high-tension turns to the number of low-tension turns in a transformer.

Reference. Karapetoff, "Experimental Electrical Engineering," Vol. I, Chap. XVI.

Apparatus. A transformer, preferably the one used in Experiment 8-A. A source of alternating current and a means of regulating the difference of potential through rather wide limits (induction voltage regulator preferred).

Method. Impress a small difference of potential on the primary and take readings of the terminal difference of potential on both sides of the transformer. Increase the supply difference of potential by steps to about 150 per cent of rated voltage. At each step take readings of the terminal difference of potential on both sides of the transformer.

Using the high-tension side as the primary, short-circuit the secondary through an ammeter of suitable range. Impress a small difference of potential on the primary and take readings of both primary and secondary currents. Increase the supply difference of potential by steps until the current in the transformer has reached about 150 per cent of rated value. At each step take readings of both primary and secondary currents.

From the readings obtained, calculate the ratio of the high-tension difference of potential to the low-tension difference of potential. Also calculate the ratio of the high-tension current to the low-tension current.

Questions. 1. How do the calculated ratios compare with the transformation ratios as given on the name plate of the transformer?

2. Explain any discrepancy which may exist.

3. If the transformer has more than one high-tension coil or more than one low-tension coil, how many possible ratios can be obtained?

4. How should the various coils be connected to obtain each of these ratios?

82. Open-circuit test. When a difference of potential is placed across the primary terminals and the secondary is left open-circuited, only the exciting current flows in the primary winding. At normal flux densities this current is very small so that the primary voltage drops (I_0r_1 and I_0x_1) are usually negligible. Therefore at no load and normal flux densities V_1 is practically equal to $-E_1$.

The $I_0^2r_1$ loss in the primary (with normal flux densities) is usually small enough to be neglected, so that the total power input to the transformer is practically equal to the core (iron) losses. The core losses are made up of hysteresis and eddy-current losses.

The angle between V_1 and I_0 can be readily determined. (See Fig. 54.) The power input divided by the V_1I_0 product equals the cosine of this angle. The core-loss component I_c of the exciting current equals the open-circuit power input divided by $-E_1$ (practically V_1). The magnetizing component I_M of the exciting current $= \sqrt{I_0^2 - I_c^2}$.

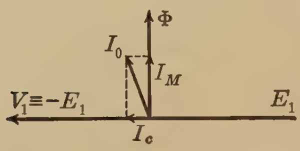

FIG. 54. No-load transformer vector diagram

The exciting current of a transformer is not a sine wave. A rheostat should not be used in the circuit between the supply difference of potential and the transformer. The voltage drop in the rheostat will not be a sine wave, and consequently such an arrangement will not give a true sine wave at the transformer terminals even though the supply difference of potential is a sine wave.

EXPERIMENT 8–C

The Open-Circuit Test of a Transformer

Object. To determine the exciting current of a transformer and to separate it into its two components, magnetizing current and core-loss current. To determine the iron losses in a transformer, and their variation with changes in the impressed difference of potential.

Apparatus. A transformer, preferably the one used in Experiment 8-A. A source of alternating current. A means of regulating the difference of potential through rather wide limits.

Method. Using the low-tension side of the transformer as the primary connect the transformer and instruments to the supply of variable difference of potential as shown in Fig. 55. Note that in this method of connections the wattmeter reads the power taken by the voltmeter as well as the power supplied to the transformer. Also that the ammeter reads the current taken by the potential coil of the wattmeter and the current taken by the voltmeter as well as the exciting current of the transformer. These errors are usually sufficiently large so that it becomes necessary to correct the instrument readings for these errors.

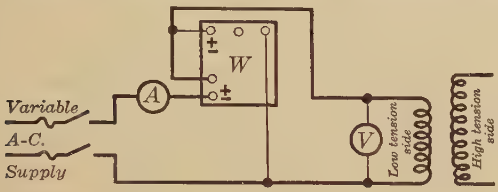

FIG. 55. Wiring diagram for the open-circuit test of a transformer

In Fig. 56, I_A = current flowing in the ammeter,

I_V = current flowing in the voltmeter,

I_W = current flowing in the wattmeter potential circuit,

P = wattmeter reading,

$$I_M = \sqrt{I_A^2 - (I_c + I_V + I_W)^2},$$

$$I_c = \frac{P}{V_1} - I_V \text{ (if } I_0^2 r_1 \text{ is negligible)},$$

and

$$I_0 = \sqrt{I_M^2 + I_c^2}.$$

The resistance of the voltmeter and of the potential circuit of the wattmeter can usually be obtained from the instruments themselves or from information published by the manufacturer of the instruments. If such information is not available, it becomes necessary to determine these resistances experimentally.

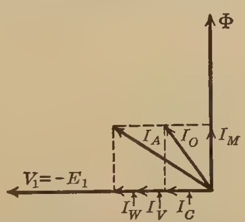

FIG. 56. Vector diagram for the open-circuit test of a transformer

Starting with a low value of supply difference of potential, take readings of the voltmeter, ammeter, and wattmeter. Increase the supply difference of potential by steps until approximately 150 per cent of the rated transformer voltage has been reached. At each step take read-

ings as above. For each reading determine the value of exciting current, magnetizing current, core-loss current, and iron loss of the transformer.

Curves. Plot curves of exciting current, magnetizing current, core-loss current, and the power necessary to supply the core loss of the transformer, as ordinates against the terminal difference of potential as abscissas.

Precautions. The variable supply of voltage should be obtained either by using a separate alternator whose field excitation can be controlled or by using an induction regulator. The supply voltage should not be controlled by means of a series rheostat. The first rush of current when the switch is closed, connecting the transformer to the supply difference of potential, may be many times the normal value of the exciting current; consequently a low-range ammeter may be seriously damaged unless it is short-circuited when the line switch is closed. (See *Precautions*, Experiment 1-A.)

Questions. 1. Would it be preferable in this experiment to use a compensated or an uncompensated wattmeter? Why?

2. Why do the curves obtained have the shape found in this experiment?

3. What other arrangement of instruments is possible?

4. Would this arrangement be more convenient than the one used in this experiment?

83. Transformer equivalent circuits. The transformer may be represented by an equivalent circuit. It can be readily shown* that for a loaded transformer

$$\overline{V}_1 = \bar{I}_0(r_1 + jx_1) + \bar{I}'\left\{\left[r_1 + \left(\frac{N_1}{N_2}\right)^2 r_2 + \left(\frac{N_1}{N_2}\right)^2 R\right] + j\left[x_1 + \left(\frac{N_1}{N_2}\right)^2 x_2 + \left(\frac{N_1}{N_2}\right)^2 X\right]\right\},$$

where $R =$ load resistance,
and $X =$ load reactance.

A circuit can be drawn that will be represented by this equation, and such a circuit will be an equivalent circuit diagram of the transformer. (See Fig. 57.)

In Fig. 57, $g_0 =$ a conductance to represent a path for I_c,
and $b_0 =$ a susceptance to represent a path for I_M.

* Christie, "Electrical Engineering," Chap. XI.

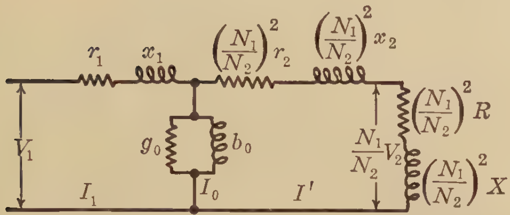

FIG. 57. Equivalent circuit diagram (referred to primary side) of a transformer

If the exciting current can be neglected, Fig. 58 may be used for the equivalent circuit diagram of a transformer. The equation for this simplified circuit is

$$\bar{V}_1 = \bar{I}'\left\{\left[r_1 + \left(\frac{N_1}{N_2}\right)^2 r_2 + \left(\frac{N_1}{N_2}\right)^2 R\right] + j\left[x_1 + \left(\frac{N_1}{N_2}\right)^2 x_2 + \left(\frac{N_1}{N_2}\right)^2 X\right]\right\}.$$

Let $R_1 = r_1 + \left(\frac{N_1}{N_2}\right)^2 r_2$. This is called the equivalent resistance (referred to primary) of the transformer. Let $X_1 = x_1 + \left(\frac{N_1}{N_2}\right)^2 x_2$. This is called the equivalent reactance (referred to

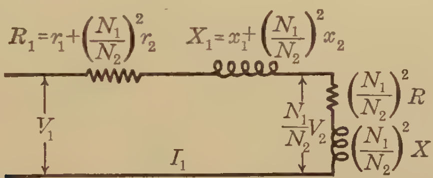

FIG. 58. Simplified equivalent circuit (referred to primary side) diagram of a transformer

primary) of the transformer. The equation for the simplified circuit (referred to primary) becomes

$$\bar{V}_1 = \bar{I}'\left\{\left[R_1 + \left(\frac{N_1}{N_2}\right)^2 R\right] + j\left[X_1 + \left(\frac{N_1}{N_2}\right)^2 X\right]\right\}.$$

By multiplying both sides of this equation by $\frac{N_1}{N_2}$ and substituting for I' its equivalent value, $\left(\frac{N_2}{N_1}\right) I_2$, the equation becomes

$$\frac{N_2}{N_1}\bar{V}_1 = \bar{I}_2\left\{\left[\left(\frac{N_2}{N_1}\right)^2 r_1 + r_2 + R\right] + j\left[\left(\frac{N_2}{N_1}\right)^2 x_1 + x_2 + X\right]\right\}.$$

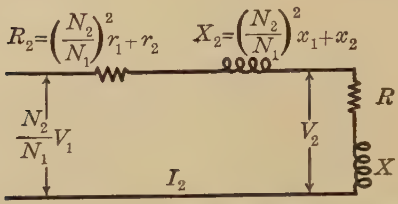

FIG. 59. Simplified equivalent circuit (referred to secondary side) diagram of a transformer

This equation is represented by the diagram shown in Fig. 59. Let $R_2 = \left(\frac{N_2}{N_1}\right)^2 r_1 + r_2$. This is called the equivalent resistance (referred to secondary) of the transformer. Let $X_2 = \left(\frac{N_2}{N_1}\right)^2 x_1 + x_2$. This is called the equivalent reactance (referred to secondary) of the transformer. The equation for the simplified circuit (referred to secondary) becomes

$$\left(\frac{N_2}{N_1}\right)\bar{V}_1 = \bar{I}_2\{[R_2 + R] + j[X_2 + X]\}.$$

84. Short-circuit test of a transformer. In this test the secondary winding is short-circuited, and a relatively low difference of potential is impressed across the primary. A voltmeter, ammeter, and wattmeter are connected into the primary circuit.

When the secondary is short-circuited, an extremely small mutual flux is necessary to produce the desired secondary electromotive force and current. Therefore the power input to the primary represents the copper losses (both windings) of the transformer and a negligibly small core loss. The short-circuit test is used for determining the copper losses of a transformer because the primary input includes the eddy-current losses in the copper windings and the additional loss due to skin effect.

The constants of the equivalent circuit of a transformer may be readily determined after the short-circuit test is made. (See Fig. 58.) In the short-circuit test R and X equal zero. Therefore the power input P divided by $(I')^2 = R_1$. (I' is practically equal to I_1 in the short-circuit test.) $X_1 = \sqrt{\frac{V_1^2 - (I'R_1)^2}{I'}}$. In the diagram shown in Fig. 59,

$$R_2 = \frac{P}{I_2^2}, \text{ and } X_2 = \sqrt{\frac{\left[\left(\frac{N_2}{N_1}\right) V_1\right]^2 - (I_2R_2)^2}{I_2}}.$$

EXPERIMENT 8-D

The Short-Circuit Test of a Transformer

Object. To determine the equivalent impedance, resistance, and reactance of a transformer.

Apparatus. The transformer used in Experiment 8-C.* A source of alternating-current supply and a means of regulating the difference of potential supplied to the transformer.

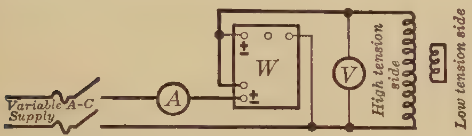

FIG. 60. Diagram of connections for the short-circuit test of a transformer

Method. Using the high-tension side of the transformer as the primary, connect the transformer and instruments to the source of variable difference of potential as shown in Fig. 60. Short-circuit the secondary of the transformer. Vary the difference of potential supplied, by steps, from a low value to a value which will cause 150 per cent of rated current to flow in the transformer. Record the temperature of the oil at the beginning and end of the test. At each step take readings of current, power, and terminal difference of potential. From these readings determine the actual power supplied to the transformer and the actual current flowing in the primary of the transformer. Calculate the equivalent impedance, resistance, and reactance of the transformer.

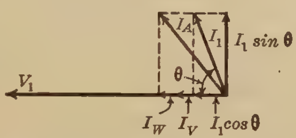

FIG. 61. Vector diagram for the short-circuit test of a transformer

In Fig. 61, I_A = current flowing in the ammeter,

I_V = current flowing in the voltmeter,

I_W = current flowing in the wattmeter potential circuit,

P = power indicated by wattmeter,

$$I_1 \sin\theta = \sqrt{I_A^2 - (I_1 \cos\theta + I_V + I_W)^2},$$

$$I_1 \cos\theta = \frac{P}{V_1} - I_V,$$

and

$$I_1 = \sqrt{(I_1 \sin\theta)^2 + (I_1 \cos\theta)^2}.$$

* It is necessary to use the same transformer in Experiments 8-C and 8-D in order that the readings taken in these experiments may be used in Experiment 8-E.

Curves. Plot curves of equivalent impedance, resistance, and reactance as ordinates against primary current as abscissas.

Questions. 1. From a theoretical consideration what should you expect the shape of the above curves to be?

2. What is the value of the iron losses in the transformer under conditions as they exist in this experiment?

3. What would be the disadvantage of using the low-tension side as the primary in this test?

85. Conventional efficiency. The efficiency of a transformer is usually determined by the conventional method because of its simplicity and accuracy. No means of loading the transformer is necessary with this method, and the amount of power required for the experiment is relatively very small.

The open-circuit test and the short-circuit test are needed to determine the efficiency of the transformer by this method. The open-circuit test (Experiment 8-C) is used for determining the core losses. The core losses are taken from the core losses-difference-of-potential curve for the normal difference of potential. It is assumed that the iron losses are constant for all loads. The short-circuit test is used for determining the copper losses. The copper losses are taken from the copper losses-current curve for the particular current to be considered. The copper losses must be corrected to 75 degrees centigrade. (See A.I.E.E. Standards, No. 13 (August, 1925), Arts. 13–303*e*.)

The transformer efficiency equals

$$\frac{\text{output}}{\text{input}}=\frac{\text{input}-\text{losses}}{\text{input}}=\frac{\text{input}-\text{losses}}{\text{output}+\text{losses}}=1-\frac{\text{losses}}{\text{output}+\text{losses}}$$

$$=1-\frac{\text{core losses}+\text{copper losses}}{V_2I_2\times\text{load power factor}+\text{core losses}+\text{copper losses}}.$$

The copper losses in the above equation must correspond to the particular output being considered. This last form of the efficiency expression is most suitable when the slide rule is being used, as one more significant figure in the efficiency can be obtained.

EXPERIMENT 8-E

The Conventional Efficiency of a Transformer

Object. To determine the conventional efficiency of a transformer from the data obtained in Experiments 8-C and 8-D.

Reference. A.I.E.E. Standards, No. 13 (August, 1925).

Method. From the readings obtained in Experiment 8-C, plot a curve of core loss as ordinates against terminal difference of potential as abscissas. From the readings obtained in Experiment 8-D (corrected to 75 degrees centigrade), plot a curve of copper loss as ordinates against current as abscissas. Using these curves, calculate the conventional efficiency of the transformer for unity power factor and for 0.6 power factor lagging.

Curves. Plot curves of efficiency as ordinates against kv-a. as abscissas.

Question. What will be the effect on the efficiency curve if the transformer is operated 10 per cent above its rated voltage?

86. Transformer regulation. The regulation of a transformer is equal to

$$\frac{V_2 \text{ (no-load)} - V_2 \text{ (rated voltage, full-load kv-a.)}}{V_2 \text{ (rated voltage, full-load kv-a.)}}.$$

The difference of potential across the primary terminals must be held constant at such a value as to produce rated secondary voltage at full load, when V_2 (no-load) and V_2 (rated voltage, full-load kv-a.) are being taken.* The power factor must be specified.

Two methods of determining transformer regulation are considered. Both methods require only the short-circuit test for the necessary calculations. The first method is given in the A.I.E.E. Standards, No. 13 (August, 1925), Arts. 13–351, and the regulation is obtained by substituting results from the short-circuit test into a simple formula. The results obtained in using the formula are very accurate. The second method of determining the transformer regulation is an exact method, but it requires considerably more calculating than the first-mentioned method.

* A.I.E.E. Standards, No. 13 (August, 1925), Arts. 13–117.

The A.I.E.E. Standards formula for transformer regulation is as follows:

$$\text{Percentage regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200},$$

where $q_r = \dfrac{I_2\,(\text{full load}) \times R_2}{V_2} \times 100$

$= \text{percentage full-load } I_2R_2 \text{ voltage drop},$

$q_x = \dfrac{I_2\,(\text{full load}) \times X_2}{V_2} \times 100$

$= \text{percentage full-load } I_2X_2 \text{ voltage drop},$

$m = \cos \theta_2,$

$n = \sin \theta_2,$

$\theta =$ load-power-factor angle,

$R_2 =$ transformer equivalent resistance (referred to secondary),

and $X_2 =$ transformer equivalent reactance (referred to secondary).

The development of the (A.I.E.E. Standards) transformer regulation is given below.

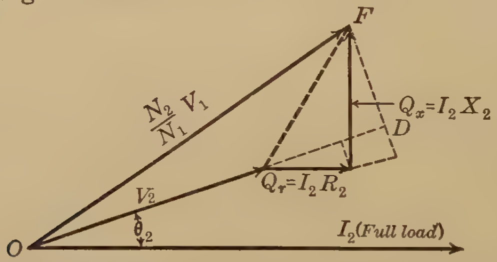

FIG. 62. Vector diagram for a transformer taken from the simplified equivalent circuit shown in Fig. 59

Fig. 62 is a vector diagram for a transformer with an inductive load. It is taken from the simplified equivalent circuit shown in Fig. 59. $\left(\frac{N_2}{N_1}\right)V_1$ is the open-circuit secondary difference of potential. Therefore the transformer regulation equals $\dfrac{\left(\frac{N_2}{N_1}\right)V_1 - V_2}{V_2}$. It is assumed that I_2 is the full-load current of the secondary winding and that V_2 is the rated difference of potential of the secondary.

Let
$$Q_r = I_2 \text{ (full load)} \times R_2,$$
$$Q_x = I_2 \text{ (full load)} \times X_2,$$
$$m = \cos \theta_2,$$
and
$$n = \sin \theta_2.$$
Then
$$OD = V_2 + mQ_r + nQ_x.$$
$$DF = mQ_x - nQ_r.$$
$$\left(\frac{N_2}{N_1}\right)V_1 = \sqrt{\overline{OD}^2 + \overline{DF}^2}$$
$$= \sqrt{(V_2 + mQ_r + nQ_x)^2 + (mQ_x - nQ_r)^2}.$$

It can be shown that, when b is small in comparison with a, $\sqrt{a^2 + b^2} = a + \frac{b^2}{2\,a}$, with an extremely small error. This is developed by means of the binomial theorem.*

Therefore
$$\left(\frac{N_2}{N_1}\right)V_1 = V_2 + mQ_r + nQ_x + \frac{(mQ_x - nQ_r)^2}{2(V_2 + mQ_r + nQ_x)}.$$

Then percentage regulation
$$= \frac{V_2 + mQ_r + nQ_x + \dfrac{(mQ_x - nQ_r)^2}{2(V_2 + mQ_r + nQ_x)} - V_2}{V_2} \times 100$$
$$= \left\{\frac{mQ_r}{V_2} + \frac{nQ_x}{V_2} + \frac{(mQ_x - nQ_r)^2}{2\,V_2(V_2 + mQ_r + nQ_x)}\right\} \times 100.$$

Let $q_r = \left(\frac{Q_r}{V_2}\right) \times 100 =$ percentage I_2R_2 voltage drop (full load),

and $q_x = \left(\frac{Q_x}{V_2}\right) \times 100 =$ percentage I_2X_2 voltage drop (full load).

Then percentage regulation
$$= mq_r + nq_x + \frac{\left[\dfrac{mq_xV_2}{100} - \dfrac{nq_rV_2}{100}\right]^2 \times 100}{2\,V_2\left[V_2 + \dfrac{mq_rV_2}{100} + \dfrac{nq_xV_2}{100}\right]}.$$

Therefore percentage regulation
$$= mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200\left[1 + \dfrac{mq_r}{100} + \dfrac{nq_x}{100}\right]}.$$

In the parenthesis, $\frac{mq_r}{100} + \frac{nq_x}{100}$ is negligible when compared to 1.

* Steinmetz, "Engineering Mathematics," p. 194. McGraw-Hill Book Company, Inc.

Therefore percentage regulation $= mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}$.

For a lagging current θ_2 is positive, and consequently m and n are positive. For leading currents θ_2 is negative, and consequently m is positive and n is negative.

For the determination of q_r and q_x the results of the short-circuit test are used. (See § 84.)

The second method of determining the transformer regulation is as follows: (See Fig. 62.)

$$\left(\frac{N_2}{N_1}\right)\bar{V}_1 = \bar{V}_2 + \bar{I}_2(R_2 + jX_2),$$

and $$\left(\frac{N_2}{N_1}\right)V_1 = \sqrt{(V_2 \cos \theta_2 + I_2R_2)^2 + (V_2 \sin \theta_2 + I_2X_2)^2}.$$

Regulation is equal to $$\frac{\left(\frac{N_2}{N_1}\right) V_1 - V_2}{V_2},$$

where V_2 = rated secondary difference of potential,
and I_2 = full-load secondary current.

The percentage regulation is equal to $$\frac{\left(\frac{N_2}{N_1}\right) V_1 - V_2}{V_2} \times 100.$$

EXPERIMENT 8-F

The Regulation of a Transformer

Object. To calculate the regulation of a transformer from the data obtained in Experiment 8-D.

References. A.I.E.E. Standards, No. 13 (August, 1925), Arts. 13-351. Christie, "Electrical Engineering," Chap. XI.

Method. From the readings obtained in Experiment 8-D calculate the percentage full-load resistance drop and the percentage full-load reactance drop. Calculate the percentage regulation of the transformer for various power factors.

Curves. Plot percentage regulation as ordinates against power factor as abscissas.

Questions. 1. At what value of power factor does maximum regulation occur?

2. At what value of power factor does zero regulation occur?

3. If R_2 had been twice as large as X_2 how would the curve have been altered?

EXPERIMENT 8–G

The Load Test of a Transformer

Object. To study the efficiency and voltage regulation of a transformer by actually loading it.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. XVI.

Apparatus. A transformer, preferably one having poor regulation. A source of alternating-current supply and some means of maintaining constant difference of potential at the primary terminals of the transformer. (An induction voltage regulator is preferable.) The necessary rheostats, inductance coils, and condensers or other suitable means of loading the transformer at different power factors.

Method. Since the variation in secondary difference of potential in the ordinary transformer is very small, it is necessary that the primary difference of potential be held constant and that the readings be taken with great care. Better results will, in general, be obtained if a transformer having abnormally poor regulation can be used. If a core-type transformer having voltage taps is available, it is sometimes possible to so unbalance the magnetic circuit as to produce a high-leakage flux and consequent poor regulation.

1. Using a resistance load, vary the secondary current by steps from zero to 150 per cent of its rated value. At each step take readings of current, power, and difference of potential on both sides of the transformer.

2. Using a highly inductive load, vary the secondary current by steps from zero to 150 per cent of its rated value. Take readings as above.

3. Using condensers only, vary the secondary current by steps from zero to 150 per cent of its rated value. Take readings as above.

4. Hold the secondary current constant at its rated value and vary the power factor, by steps, through as wide limits as possible. Take readings as above.

Curves. In each case plot curves of efficiency and secondary difference of potential as ordinates against the independent variable as abscissas. Also plot a curve of per-cent regulation against power factor.

Questions. 1. Which do you consider the more accurate, the conventional efficiency or the directly measured efficiency?

2. Which do you consider the more accurate, the regulation as determined by the method used in the A.I.E.E. Standards or the regulation as determined in this experiment?

EXPERIMENT 8–H

Opposition Test using Two Transformers

Object. To determine the temperature rise of a transformer by using the opposition method of loading.

Reference. A.I.E.E. Standards, No. 13 (August, 1925).

Apparatus. Two transformers having the same ratio of turns, the one to be tested and the other sufficiently large for loading the transformer under test. Two induction voltage regulators or, if these are not available, two current-limiting rheostats.

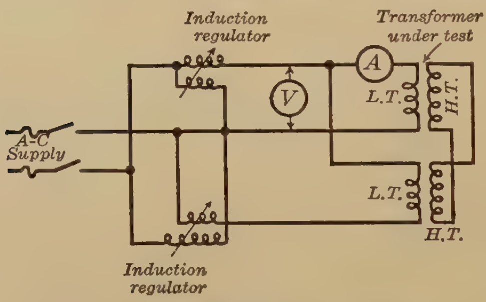

FIG. 63. Two transformers connected in opposition

Method. Measure the resistances of the high-tension and the low-tension windings. Record the temperature of the oil. Connect the apparatus as shown in Fig. 63. Adjust the low-tension difference of potential to rated value, and the low-tension current to rated value. Maintain these values constant throughout the test. Take readings as specified in A.I.E.E. Standards, Arts. 13–211*c*. Also take readings of the temperature of the oil immediately above the coils. Take these temperature readings every half hour till near the end of the test, when temperature readings should be taken every 15 minutes. When three successive temperature readings show constant temperature, disconnect the transformer and again measure the resistances of the high-tension and the low-tension windings. Calculate the temperature rise from the resistance measurements.

Considerable time can be saved in making this test if the transformer is overloaded during the first few hours of the test.

Precautions. For reading oil temperature, it is preferable to use an alcohol thermometer because the breaking of a mercury thermometer may damage the transformer.

Curves. Plot a curve of oil temperature versus time.

Questions. 1. Why does the temperature determined from resistance measurements differ from the temperature as determined by the thermometer immersed in the oil?

2. Does the temperature of the transformer stay within allowable limits?

87. Separation of core losses. The core losses of a transformer are made up of the eddy-current loss and the hysteresis loss. It is often desirable to separate these losses.

The eddy-current loss $P_e = k_e V t^2 f^2 B_M^2$ watts, where

k_e = a constant which depends upon the quality of the iron and the units used,

V = volume of iron,

t = thickness of laminations,

f = frequency in cycles per second, and

B_M = maximum flux density.

The hysteresis loss $P_h = k_h V f B_M^{1.6}$ watts, where

k_h = a constant which depends upon the quality of the iron and the units used.

Therefore, for a given transformer the core losses

$$P_e + P_h = k_e' f^2 B_M^2 + k_h' f B_M^{1.6} \text{ watts,}$$

where k_e' and k_h' are constants.

It can be readily shown that $E_1 = \sqrt{2}\,\pi N_1 f A B_M \times 10^{-8}$ volts, where A = area of cross section of the magnetic circuit.

Therefore $B_M = \dfrac{kE_1}{f}$ for a given transformer, where k is a constant.

V_1 and E_1 have practically the same numeric values when the transformer is being tested in the open-circuit test, so that B_M is very nearly equal to $\dfrac{kV_1}{f}$.

To separate the core losses an open-circuit test is made. The value of $\frac{V_1}{f}$ is held constant so that B_M remains constant. Both V_1 and f are varied over a comparatively wide range. The core losses then equal $k_e''f^2 + k_h''f$, where k_e'' and k_h'' are constants. It will be noted that

$$\frac{P_e + P_h}{f} = k_e''f + k_h''.$$

This equation, if plotted, is a straight line. (See Fig. 64.) If the straight line is projected to the $\frac{P_e + P_h}{f}$ axis, the ordinate at this axis will be k_h''. This value when multiplied by the rated frequency will give the hysteresis loss of the transformer at that frequency. The eddy-current loss can be determined by taking the ordinate of the curve (Fig. 64) corresponding to the rated frequency and, after subtracting from it k_h'', multiplying the remainder by f. In Fig. 64 at the frequency F the hysteresis loss equals $k_h''F$ and the eddy-current loss equals $(k_e''f)F$. These calculated losses correspond to the flux density that was used in the test.

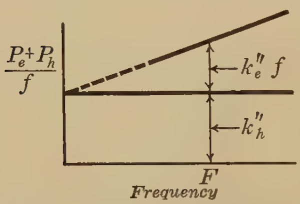

FIG. 64. Curve for separation of eddy-current and hysteresis losses in a transformer

The eddy-current loss and the hysteresis loss may be determined for a single frequency by a simple method. Measure the core-loss input to the transformer with the desired frequency at two differences of potential, differing from each other by a considerable amount. Then let the subscript A refer to the first difference of potential and let the subscript B refer to the second difference of potential. Let $P_1 =$ the power input for case 1, and let $P_2 =$ the power input for case 2. Then

$$P_1 = k_e'''V_A^2 + k_h'''V_A^{1.6},$$

and $$P_2 = k_e'''V_B^2 + k_h'''V_B^{1.6},$$ where k_e''' and k_h''' are constants.

The above equations are true because the frequency is held constant, and therefore the impressed difference of potential is practically proportional to B_M. There are two unknowns (k_e''' and k_h''') in the above two equations and they may be readily deter-

mined. The eddy-current loss at the rated difference of potential will be k_e''' times the square of the rated difference of potential. The hysteresis loss at the rated difference of potential will be k_h''' times the 1.6th power of the rated difference of potential.

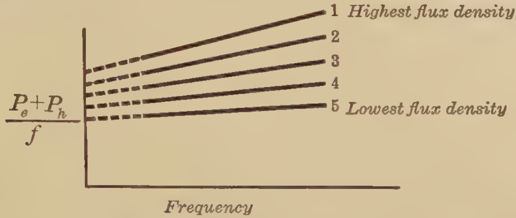

FIG. 65. Curve for separation of eddy-current and hysteresis losses in a transformer at different flux densities

88. The Steinmetz exponent. The hysteresis loss in iron $P_h = k_h V f B_M^x$ watts, where x is supposedly unknown in the experiment. The quantity x is called the Steinmetz exponent.

It is necessary that P_h be known for different flux densities, in order to determine the value of x. To determine P_h for different flux densities it will be necessary to obtain several sets of readings. Each set of readings must be taken at a constant flux density and there must be sufficient data for plotting the curve shown in Fig. 64. A wide range of flux densities should be used, so that a family of curves similar to the curve shown in Fig. 64 may be drawn. (See Fig. 65.) From the curves which are shown in Fig. 65 determine P_h at some particular value of frequency (preferably the rated frequency) for each flux density.

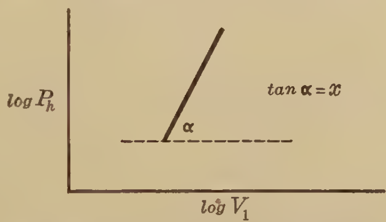

FIG. 66. Curve for determining the Steinmetz exponent. The abscissa and ordinate scales are equal

If the frequency of a transformer is held constant, and the impressed difference of potential V_1 is varied, the maximum flux density B_M will vary directly with V_1. Therefore the newly calculated values of $P_h = k_h'''V_1^x$.

Then $$\log P_h = \log k_h''' + x \log V_1.$$

A curve with the values of $\log P_h$ plotted as ordinates and the values of $\log V_1$ plotted as abscissas is a straight line. (See Fig. 66.)

The Steinmetz exponent x will be equal to $\Delta(\log P_h)$ divided by $\Delta(\log V_1)$. This is the slope of the curve. If equal scales are used for the abscissa and ordinate axes, the Steinmetz exponent equals tan α. The angle that the straight line makes with the horizontal is α, and it is so labeled in Fig. 66.

EXPERIMENT 8-I

The Separation of Iron Losses in a Transformer

Object. To separate the hysteresis and eddy-current losses in a transformer, and to determine experimentally the Steinmetz exponent.

References. Swenson & Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. II, Exps. 41 and 42.

Karapetoff, "Experimental Electrical Engineering," Art. 223.

Apparatus. A transformer. An alternator driven by an adjustable-speed motor so that a wide range of frequencies can be obtained.

Method. Connect the low-tension side of the transformer to the alternator and insert a wattmeter to measure the power supplied to the transformer. Take several sets of readings at different flux densities. The following flux densities are suggested: 50 per cent, 75 per cent, 100 per cent, 125 per cent, and 150 per cent of normal value. For each set of readings, vary frequency through as wide limits as possible. For any one set of readings, hold flux density constant. In general the $I_0^2r_1$ loss in the transformer will be negligible and the power input to the transformer can be taken as the core loss. If the $I_0^2r_1$ loss is not negligible, a suitable correction should be made.*

Precautions. See *Precautions*, Experiment 8-C.

Curves. Plot curves of $\frac{P}{f}$ as ordinates against f as abscissas for at least five values of flux densities. Plot curves of P_e and P_h as ordinates against f as abscissas for normal flux density. Plot a curve of log P_h against log V_1 and from this determine the Steinmetz exponent.

* If the transformer under test has two identical low-tension coils, the $I_0^2r_1$ loss can be eliminated from the wattmeter reading by using one low-tension coil as the primary and by impressing the induced electromotive force of the other low-tension coil on the potential circuit of the wattmeter.

89. Three-wire transformers. Distribution transformers are usually three-wire transformers, because they offer the advantage of a large saving in the amount of copper needed for the distributing system. The voltage regulation for distribution transformers must be good in order to supply at all times a proper difference of potential to the lighting loads of the customers.

A sketch of a simple core-type three-wire transformer is shown in Fig. 67. In this figure one half of the primary winding is

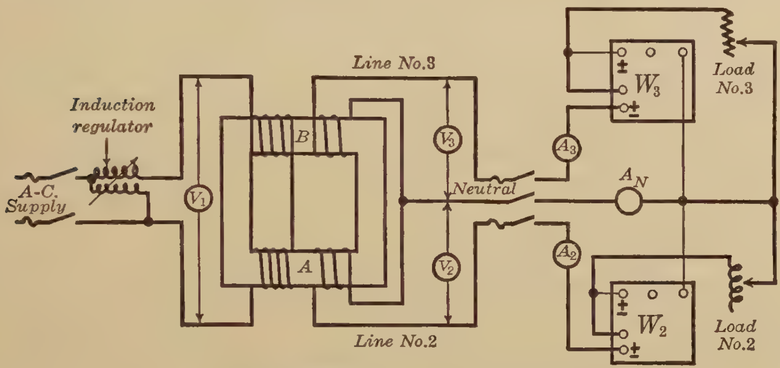

FIG. 67. Wiring diagram for a three-wire transformer

placed on the core leg *A*, and the other half of the primary winding is placed on the core leg *B*. These windings are connected in series. Correspondingly one half of the secondary winding is placed on each core leg.

If the transformer shown in Fig. 67 is loaded with identical loads on the two sides of the secondary, the difference of potential between the secondary lines No. 2 and No. 3 will be twice that of the difference of potential between either line No. 2 or No. 3 and the neutral wire *N*. For such a load the current in the wire *N* will be zero. The magnetomotive forces of the coils will be balancing each other so that the resulting difference of magnetic potential between the ends of the legs will be zero. A vector diagram similar to the diagram shown in Fig. 53 can be drawn to represent this condition.

When such a transformer does not have identical loads on the two sides, a somewhat different vector diagram must be used to represent the results. Fig. 68 is a vector diagram for the three-wire transformer. In the diagram the following notation is used:

Φ_M = mutual flux,

$\Phi_T(\text{leg } A)$ = total flux that is common to the primary and secondary coils on core leg A,

$\Phi_T(\text{leg } B)$ = total flux that is common to the primary and secondary coils on core leg B,

E_2 = electromotive force induced in the secondary coil that is located on core leg A,

E_3 = electromotive force induced in the secondary coil that is located on core leg B,

V_2 = difference of potential between line No. 2 and the neutral wire N,

V_3 = difference of potential between line No. 3 and the neutral wire N,

I_3 = current in the secondary coil that is located on core leg B,

and $\dfrac{N_1}{N_2} = 1.$

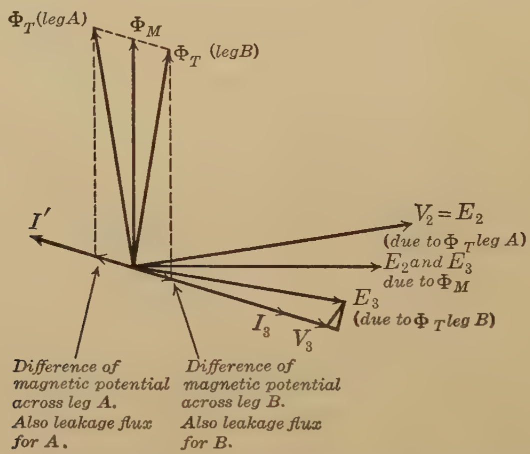

FIG. 68. Vector diagram for three-wire transformer. Resistance load on one side and no load on the other side

The load current for line No. 2 equals zero. The load current for line No. 3 is in phase with the difference of potential V_3.

The difference of magnetic potential across the core legs is not zero for this unbalanced loading. Consider the core leg B. The number of ampere turns on the secondary winding is twice the number of ampere turns on the primary (neglecting the mag-

netomotive force of the exciting current). Therefore there is a difference of magnetic potential across the core leg B which is in phase with I_3. There is set up in the core leg B a corresponding leakage flux which threads both the primary and secondary turns on that leg. As a result the total flux in core leg B is reduced. This is shown in the vector diagram. Therefore the value of E_3 is reduced, and shifted clockwise to keep the 90-degree relation with the total flux in that core leg. To obtain V_3 it will be necessary to subtract the impedance drop for this secondary winding. This impedance drop is made up, first, of the I_3r_3 drop, where r_3 is the resistance of the secondary winding on core leg B; second, of the I_3x_3 drop, where x_3 is the leakage reactance of the secondary winding on core leg B due to the leakage flux that threads only that secondary coil.

The ampere turns on the primary of the core leg A are not balanced by any ampere turns on the same leg. Therefore the magnetomotive force produced tends to set up leakage flux that threads the primary as well as the secondary windings on core leg A. The total flux in core leg A is increased. This is shown in the vector diagram. Correspondingly E_2 becomes greater. Note that it is also shifted counterclockwise to keep the 90-degree relation with the total flux in core leg A. There is no voltage drop in the secondary coil on core leg A, so $E_2 = V_2$.

The diagram shows that when a three-wire transformer is loaded in this way, the difference of potential across the loaded side decreases, and the difference of potential across the unloaded side increases.

Fig. 69 is a vector diagram that represents the same three-wire transformer loaded with a resistance load on side No. 3 and an inductive load on side No. 2. To make the diagram clearer, the exciting-current vector is omitted. Note that the numeric values of I_2 and I_3 are the same, where

$$I_2 = \text{current in line No. 2,}$$

and $$I_3 = \text{current in line No. 3.}$$

The current I' is the vector sum of the load components of the primary current produced by I_2 and I_3. The difference of magnetic potential across each leg is the vector sum of the magnetomotive forces of the two coils on the particular leg considered. As will be noted in the diagram, the total flux in core leg B

will be greater than the total flux in core leg A. The voltages E_2 and E_3 are placed 90 degrees behind Φ_T(leg A) and Φ_T(leg B) respectively. To obtain V_2 and V_3 it is necessary to subtract properly the impedance drops.

The diagram in Fig. 69 shows that when a three-wire transformer is loaded in the way indicated above, the difference of

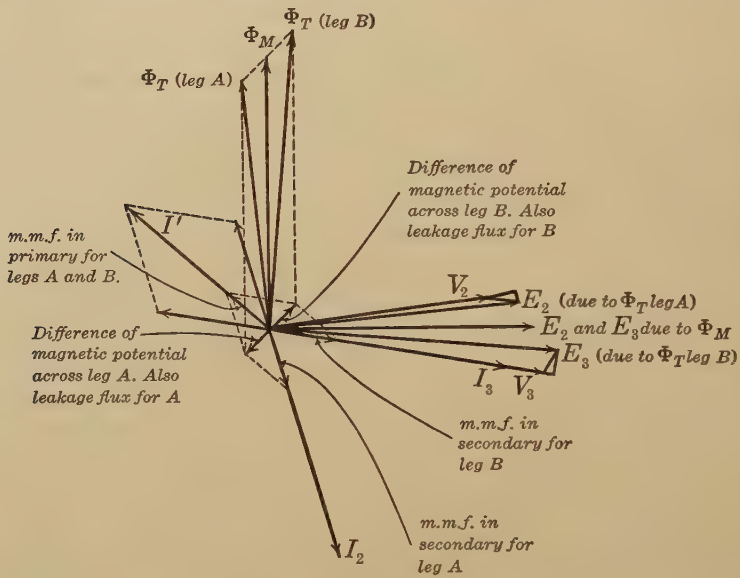

FIG. 69. Vector diagram for three-wire transformer. Resistance load on one side and inductive load on the other

potential across the resistance load will be greater than the difference of potential across the inductive load, even though the load currents are the same.

A core-type three-wire transformer has been assumed for simplicity in this article. The same reasoning applies to the other types of transformer cores. If the two secondary windings are closely coupled, the differences of potential on the two sides of the secondary will be very nearly equal under all conditions of loading.

The high-efficiency type of transformer, consisting of a cruciform core and a distributed shell, is particularly suitable for three-wire distribution because all the coils are closely coupled on the central core leg.

EXPERIMENT 8–J

The Three-Wire Transformer

Object. To study the voltage regulation of a transformer supplying a three-wire load under various conditions of loading.

Apparatus. A transformer having two identical secondary coils so that it can be used as a three-wire transformer. (Preferably a core-type transformer having one secondary coil on each leg.) A source of alternating-current supply and some means of holding constant primary difference of potential. The necessary apparatus for loading the transformer at different power factors.

Method. Connect the transformer as shown in Fig. 67.

1. With one side unloaded and a resistance load on the other side, vary the load by steps from zero to 150 per cent of rated secondary current. Maintain the primary difference of potential constant.

2. With resistance load on one side held constant at rated value, vary the load on the other side as in the first part.

3. With a resistance load on one side held constant at rated value, vary the power factor on the other side through as wide limits as possible. Maintain the secondary currents and the primary difference of potential constant at their rated values.

Curves. Plot the necessary curves to illustrate your results.

Question. How would the curves be altered if the two primary coils were connected in parallel instead of in series?

90. Constant-current transformer. A constant-current transformer is a specially constructed transformer for maintaining constant current in the secondary with a variable load, while the difference of potential across the primary winding is held constant.

Fig. 70 shows the general form of a constant-current transformer. The secondary is the movable coil. The primary is the fixed coil. The weight is so adjusted that it almost balances the weight of the movable coil, and correspondingly when the transformer is not in use the secondary coil will settle until it rests on the primary coil if it is not held to the top by some mechanical means.

When a difference of potential is impressed across the primary terminals, electromotive forces will be induced in both the pri-

mary and secondary. The mutual flux will be greatest when the movable coil is resting on the primary. If the secondary is lifted the primary leakage flux becomes greater and the mutual flux is correspondingly decreased. This decreases E_2 (the electromotive force induced in the secondary due to mutual flux).

If a current is allowed to flow in the secondary, a corresponding load component of current is drawn in the primary. These currents are 180 degrees apart and therefore the coils will repel each other, and the greater the currents, the greater will be the repulsion.

The transformer operates as follows. Assume a particular load attached to the secondary, and the secondary floating in a mid position. Let the external load resistance be increased (for example, insert more lamps in the series circuit). Then the current decreases. The coil repulsion is decreased and the secondary coil settles. The leakage flux becomes less, and the mutual flux becomes greater. Therefore E_2 increases, and I_2 (secondary current) is increased. This movable coil settles until there is a new balance of mechanical forces; when this balance is reached, the coil will be in a lower position, I_2 will be slightly less than the original secondary current, and V_2 will be considerably greater. If the load resistance had been decreased the movable coil would have taken a higher position, I_2 would have been slightly increased, and V_2 would have been considerably decreased.

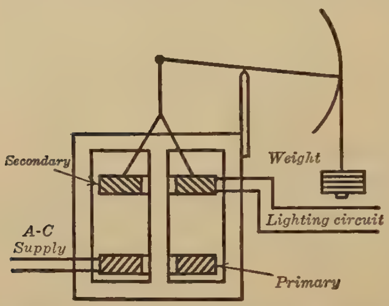

FIG. 70. Sketch of a constant-current transformer

When the transformer is in operation and carrying no load, the secondary terminals will be short-circuited ($V_2 = 0$), and the movable coil will be at the top. At the maximum load the secondary current will be slightly less than the secondary current at no load, V_2 will be a maximum, and the movable coil will be resting on the primary.

EXPERIMENT 8-K

The Constant-Current Transformer

Object. To study the operating characteristics of a constant-current transformer.

References. Karapetoff, "Experimental Electrical Engineering," Art. 412.

Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. II, Exp. 40.

Apparatus. A constant-current transformer and suitable means of loading. A source of alternating-current supply and some means of maintaining constant difference of potential at the terminals of the primary.

Method. Connect instruments so as to measure current, difference of potential, and power on each side of the transformer.

1. Holding constant primary difference of potential, vary the secondary load resistance from zero to infinity, taking readings of all instruments at suitable intervals. Place a scale on the core of the transformer and note the position of the movable coil at each interval.

2. Use an inductive load and investigate the effect of power factor on the performance of the transformer.

3. Investigate the ability of the transformer to maintain constant current when the load resistance is changed suddenly.

Precautions. Since high potentials are involved in this experiment, the necessary precautions should be taken.

The movable coil should always be held in the top position until the transformer switches are closed. Then lower the movable coil slowly until it takes its free position.

Curves. Plot curves of efficiency, primary and secondary currents, primary and secondary power factors, and secondary difference of potential as ordinates against kv-a. output as abscissas. Plot a curve of secondary difference of potential versus position of the movable coil.

Questions. 1. How would per-cent regulation be defined for a constant-current transformer?

2. How might the regulation of the transformer be improved?

3. How could the transformer be made more sensitive to sudden changes in load?

91. Instrument potential transformers. Instrument potential transformers are used for transforming high alternating differences of potential to relatively low differences of potential that are suitable for measuring instruments. They also serve to insulate the instrument circuits from the high-tension wires.

An instrument potential transformer is very similar to any constant potential transformer. It is designed for a relatively low output as the power required by a few measuring instruments is small. Low flux densities are used in the iron to prevent distortion in the secondary electromotive-force wave. The impedance drops of the instrument potential transformer are made very small so that when the primary difference of potential V_1 is varied, the ratio of V_1 to the secondary difference of potential V_2 will be practically constant and the phase angle between V_1 and V_2 will remain nearly 180 degrees.

On account of the impedance drops in the transformer, $\frac{V_1}{V_2}$ will always be greater than $\frac{N_1}{N_2}$ (see Fig. 53) when a meter load is attached. The instrument potential transformer is compensated for a particular load (R and X in the secondary). In other words, usually a few turns are removed from the primary or a few turns are added to the secondary, so that $\frac{V_1}{V_2}$ is almost equal to the rated ratio when a particular meter load is placed on the transformer and V_2 is the rated value. If V_2 is changed, or if a different secondary load resistance and reactance are used, $\frac{V_1}{V_2}$ differs from the rated value, and if high accuracy is desired a correction factor must be used.

The value of the correction factor will depend upon the secondary difference of potential, the frequency, and the number and kind of instruments connected into the secondary circuit. The correction factor is usually plotted as ordinates against secondary volts as abscissas for a specified secondary load impedance. Fig. 71 gives typical correction curves for an instrument potential transformer. If the power factor of the secondary circuit becomes less (lagging current assumed), the correction factor will be larger.

Phase-angle corrections do not apply to voltmeter readings, but they do apply to wattmeter and power-factor-meter

readings. Fig. 72 gives typical phase-angle correction curves for a particular instrument potential transformer. The ordinates represent the angle between the secondary difference of potential and the primary difference of potential, reversed.

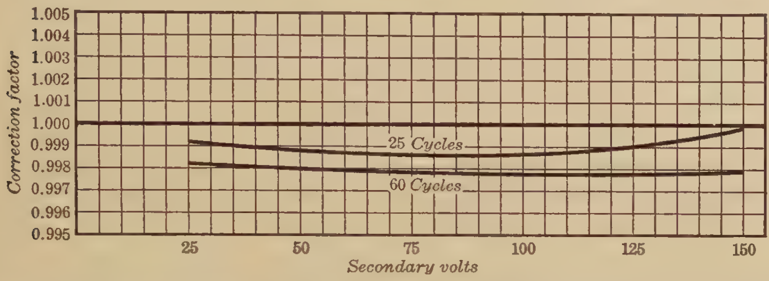

FIG. 71. Ratio-correction curves for Weston Model 311 portable instrument potential transformer. Secondary load — Weston portable voltmeter and wattmeter

When the instrument potential transformer is used with a wattmeter in a circuit where the power factor is high, the phase-angle correction may usually be omitted, even though very accurate results are desired. For example, $\cos 2° = 0.9994$, $\cos 3° = 0.9985$. Therefore a phase-angle error of one degree

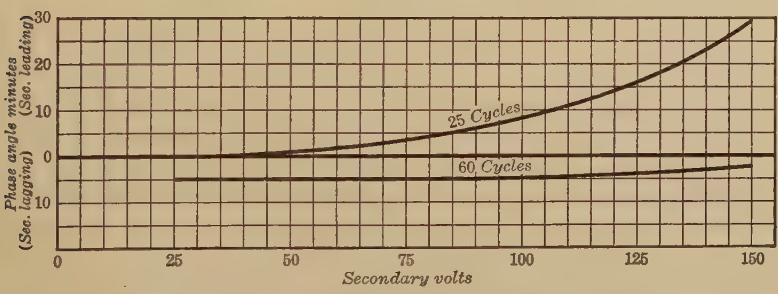

FIG. 72. Phase-angle curves for Weston Model 311 portable instrument potential transformer. Secondary load — Weston portable voltmeter and wattmeter

affects the indication by less than 0.1 per cent. However, if the power factor of the circuit is low, an error of one degree leads to a considerable error in the measured power. For example, $\cos 60° = 0.5000$, $\cos 61° = 0.4848$, the error being 3 per cent. The phase-angle shift of a good instrument potential trans-

former is less than one degree, but when used in circuits where the power factor is low this error must be taken into account if very accurate results are desired.

92. Instrument current transformers. Instrument current transformers, commonly called current transformers, are used for transforming large currents to relatively small currents that are suitable for measuring instruments, and also to insulate the instrument circuits from high-tension wires.

The current transformer is designed for a relatively low output as the power required by a few instruments is small. The full-load secondary current is usually 5 amperes, and a common full-load output is 50 volt-amperes, with compensation for 25 volt-amperes.

In an ideal current transformer the ratio of primary to secondary current would remain constant as the primary current is varied, and the angle between the secondary current I_2 and the primary current I_1 would be 180 degrees for all current values. However, in the actual current transformer the exciting current I_0 causes the ratio of the primary to secondary current to vary with the secondary current and the power factor of its secondary load, and it also causes a phase shift from the desired 180-degree relation of the primary and secondary currents. For these reasons I_0 is kept low by using a high-permeability low-loss iron that is well laminated, and by designing the secondary winding with a very low impedance. The lower the secondary impedance is made, the lower the secondary electromotive force E_2 must be to produce a given secondary current, and, correspondingly, the mutual flux and I_0 will be smaller.

If the power factor of the secondary circuit is reduced (instruments introduced into the circuit with a relatively large reactance), the exciting current will be more nearly in phase with the total primary current I_1, and therefore the phase-angle error is smaller and the ratio error is larger.

On account of the exciting current I_0, $\frac{I_1}{I_2}$ will always be greater than $\frac{N_2}{N_1}$, and as the power factor of the secondary circuit is decreased from unity, $\frac{I_1}{I_2}$ will increase and reach a maximum when I_2 is in phase with I_0. The instrument current transformer is compensated for a particular burden (value of

R and X in the secondary) and full-load secondary current. In other words, usually one or two turns are added to the primary, or a few turns are removed from the secondary, so that $\frac{I_1}{I_2}$ is almost equal to the rated ratio when a particular meter load is placed in the secondary circuit and I_2 is the rated value. If I_2 is changed, or if a different secondary load resistance and reactance are used, $\frac{I_1}{I_2}$ differs from the rated ratio, and if high accuracy is desired a correction factor must be used.

The value of the correction factor will depend upon the secondary current, frequency, and the number and the kind of

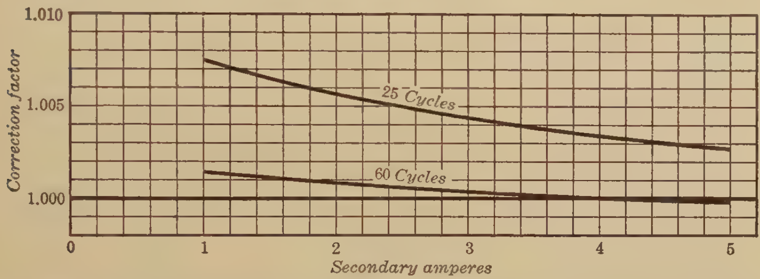

FIG. 73. Ratio-correction curves for Weston Model 461 portable multi-range instrument current transformer. Secondary burden — Weston portable ammeter and wattmeter

instruments connected into the secondary circuit. The correction factor is usually plotted as ordinates against secondary current as abscissas for a specified secondary load impedance. Fig. 73 gives typical correction curves for a current transformer. If the power factor of the secondary circuit is decreased from unity (lagging current assumed), the correction factor will increase until a maximum is reached when I_1 is in phase with I_0. When an instrument transformer is used in a 60-cycle circuit the correction factor is smaller than the corresponding correction factor that must be used if the transformer is used in a 25-cycle circuit. The flux and exciting current will be greater for a given volt-ampere load in the 25-cycle circuit.

Phase-angle corrections do not apply to ammeter readings, but they do apply to wattmeter and power-factor-meter readings. Fig. 74 gives typical phase-angle correction curves for an

instrument transformer. The ordinates represent the angle between the secondary current I_2 and I_1, reversed.

When the instrument current transformer is used with a wattmeter in a circuit where the power factor is high, the phase-angle correction may usually be omitted even where accurate results are desired. (See Experiment 8-L.) However, if the current transformer is used with a wattmeter in a circuit where the power factor is low, this error must be taken into account if very accurate results are desired.

The total current in the primary of an instrument current transformer becomes the exciting current of the transformer if

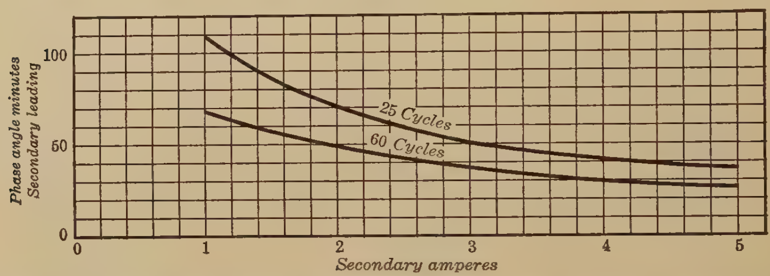

FIG. 74. Phase-angle curves for Weston Model 461 portable multi-range instrument current transformer. Secondary burden — Weston portable ammeter and wattmeter

the secondary is open-circuited. The mutual flux becomes large, and as the iron core is designed to carry only a small value of flux, the core will become hot due to large iron losses. The transformer is then a step-up transformer and the secondary difference of potential may be dangerously high.

The secondary should be provided with a short-circuiting link which must be closed before the secondary circuit is opened. If high flux densities are produced accidentally in the core at any time, it will be necessary to demagnetize the core before it is used again. If the current transformer is not demagnetized, considerable error will exist in the readings of the instruments that are placed in its secondary circuit. The current transformer core may be demagnetized by passing an alternating current of approximately rated value through either winding with the other winding open-circuited, and gradually reducing the current to zero.

EXPERIMENT 8-L

Instrument Current Transformers

Object. To study some of the characteristics of a current transformer and to determine the effect of adding resistance or inductance in its secondary circuit.

Reference. Laws, "Electrical Measurements," Chap. XII.

Apparatus. A current transformer. A current-limiting rheostat for controlling the primary current. A variable resistance and inductance for use in the secondary circuit of the transformer.

Method. 1. Place an ammeter in series with the primary and short-circuit the secondary through an ammeter. Vary the primary current by steps from zero to 150 per cent of rated full-load value. At each step take readings of primary and secondary currents.

2. Repeat the above, using the low-current winding as the primary. (Transformer reversed.)

3. With the transformer connected as in part 1, and full-load current held constant in the primary, increase the resistance of the secondary circuit by steps until the current ratio has been changed approximately 10 per cent. At each step take readings of primary and secondary currents.

4. Repeat part 3, using inductance in the secondary circuit.

5. With the secondary open-circuited, place voltmeters across the terminals of both the primary and secondary windings. Take readings of primary current, primary difference of potential, and secondary difference of potential for different values of primary current from zero to rated value.

6. Demagnetize the iron of the current transformer so that it will be in condition for future use.

Precautions. The secondary difference of potential in part 5 may be dangerously high. Do not allow the temperature of the transformer to become excessive.

Curves. For each part of the experiment, plot the necessary curves to illustrate your results.

Questions. 1. If the secondary circuit of a current transformer is opened, what will be the effect upon the primary circuit?

2. What will be the effect upon the current transformer?

3. Why should the secondary of a current transformer be grounded when the primary is used in a high-potential circuit?

4. What determines the maximum value which the secondary difference of potential may reach on open circuit?

5. What are the relative effects of secondary resistance and inductive reactance on the transformer ratio?

6. On the phase angle of the transformer?

93. Three-phase transformer connections. The following are the most common methods in which transformers may be connected for three-phase transformation.

PRIMARY	SECONDARY
Delta	Delta
Delta	Y
Y	Delta
Y	Y
Open delta	Open delta

scott

94. The delta-delta transformer connection with single-phase transformers. If single-phase transformers are used, three transformers will be needed for the delta-delta transformer connection. Fig. 75 represents the delta-delta transformer connection. The line differences of potential are equal to the transformer differences of potential. The secondary difference of potential V_2

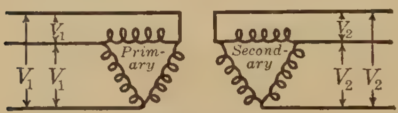

FIG. 75. Delta-delta transformer connection

approximately equals $\left(\frac{N_2}{N_1}\right) V_1$,

where $N_1 =$ primary turns on one transformer,
and $N_2 =$ secondary turns on one transformer.

For a balanced load the line currents equal the transformer currents multiplied by $\sqrt{3}$. In other words, delta-delta transformers must be designed for full line difference of potential but for only 57.7 per cent of the line current.

Two disadvantages of the delta-delta transformer connection are, first, the neutral cannot be easily obtained; secondly, six high-voltage transformer bushings are required. One advantage of this system is that in the event that one of the three trans-

formers is inoperative, the other two transformers may be used in the open-delta connection. (See § 98.)

95. The delta-Y transformer connection with single-phase transformers. Fig. 76 represents the delta-Y transformer connection. The voltage and current relations of the primary are the same as in the delta-delta connection. On the secondary side the line-to-line voltages are equal to the transformer voltages multiplied by $\sqrt{3}$. In other words, V_2 approximately equals $\sqrt{3}\left(\frac{N_2}{N_1}\right)V_1$. The line currents are equal to the transformer currents. With this connection the number of secondary turns is 57.7 per cent of that required for the delta secondary, but the cross section of the conductors must be correspondingly greater for the same output.

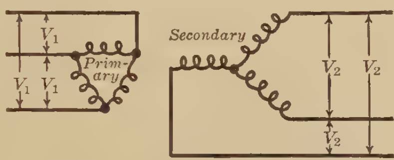

FIG. 76. Delta-Y transformer connection

This connection is used to a considerable extent. It is very convenient for supplying distributing systems in that a fourth wire may be led from the neutral point of the secondaries.

A common distribution voltage for lighting loads is 2300 volts. If a line-to-neutral voltage of 2300 volts is used in a three-phase four-wire system, the resulting line-to-line voltage will be 4000 volts. This system has the advantage that standard 2300-volt transformers may be used, and in addition has the copper economy of a 4000-volt system.

Two advantages of the delta-Y connection for a step-up transformer bank are, first, only three high-tension bushings are needed; secondly, the neutral on the high-tension side is available for grounding.

96. The Y-delta transformer connection with single-phase transformers. In this connection the voltage and current relations of the primary correspond to the secondary relations of the delta-Y connection, and the voltage and current relations of the secondary correspond to the primary of the delta-Y connection.

Therefore V_2 approximately equals $\dfrac{V_1\left(\frac{N_2}{N_1}\right)}{\sqrt{3}}$.

The Y-delta connection is sometimes used at the receiving end of transmission lines. One advantage for a step-down transformer is that only three high-tension bushings are needed.

97. The Y-Y transformer connection with single-phase transformers. Fig. 77 represents the Y-Y transformer connection. The line voltages are equal to the transformer voltages multiplied by $\sqrt{3}$. The line currents are equal to the transformer currents, and V_2 approximately equals $\left(\frac{N_2}{N_1}\right) V_1$. With this connection both primary and secondary windings are designed for full line current and 57.7 per cent of the line voltage.

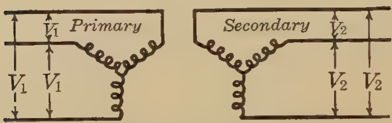

FIG. 77. Y-Y transformer connection

This connection is seldom recommended for a bank of three-phase transformers. This is due to the fact that the third and the odd multiples of the third harmonics of exciting current cannot flow if the neutrals of the primary and source of supply are not grounded or electrically connected. If the neutrals of the primary and the source of supply are not electrically connected the third and the odd multiples of the third harmonics will appear in the flux and electromotive-force waves of the transformers. However, no third or multiples of the third harmonics will appear in the waves of the line-to-line differences of potential.

The third and the odd multiples of the third harmonics appearing in the electromotive-force and difference-of-potential waves of the transformer secondaries may produce excessive stresses in the winding insulation. If the neutrals of the primary and the source of supply are grounded, the insulation stresses will become small, but the ground currents are apt to cause serious interference in parallel telephone lines.

EXPERIMENT 8–M

Delta and Y Transformer Connections

Object. To study the electrical relations which exist in the various combinations of delta and Y transformer connections.

Reference. Karapetoff, "Experimental Electrical Engineering," Chaps. XXXVIII, XXXIX, XL, XLI.

Apparatus. Three identical single-phase transformers. A three-phase Y-connected alternator with its neutral available. The necessary rheostats for loading the transformers. Suitable instruments.

Method. It is preferable that a sufficient number of wattmeters be connected on each side of the transformer bank so that the phase angles between the various quantities can be determined.

1. Connect the transformers delta-delta. Study the relations which exist between the line currents and the currents in the various transformer windings under different conditions of balanced load. With no load on the secondary, insert an ammeter in one corner of the secondary delta and note the circulating current in the delta.

2. Connect the transformers delta-Y. Study the relations which exist between the line currents and the currents in the transformer windings on both the primary and secondary sides. Also observe the relations which exist between the transformer voltages and the line-to-line voltages.

3. Connect the transformers Y-delta. Connect the neutral of the transformer bank to the neutral of the alternator. Place an ammeter in this neutral connection and note the current flowing. Determine the circulating current in the secondary delta. Open the neutral connection and again note the circulating current in the secondary delta. Also note the difference of potential between the neutral of the transformer bank and the neutral of the alternator.

Load the transformers with a balanced load and study the relations existing between the various currents and voltages on the two sides of the transformers.

4. Connect the transformers Y-Y. Connect an ammeter between the neutral of the transformer bank and the neutral of the alternator. Study the relations which exist between the various currents and voltages on the two sides of the transformers when a balanced load is applied to the secondary. Open the neutral connection and repeat. Be sure to observe the difference of potential between the neutral of the transformer bank and the neutral of the alternator.

5. If time permits, study these various connections with unbalanced loads on the secondary side.

Questions. 1. Why does a current sometimes circulate in the closed delta of the secondary when there is no load on the transformers?

2. Why does a difference of potential exist between the primary neutral of the transformer bank and the neutral of the alternator?

3. With what connections is the difference of potential between the primary neutral of the transformer bank and the neutral of the alternator large? Small?

4. What is the nature of the current flowing in the neutral connection when the primary neutral of the transformer bank is connected to the neutral of the alternator?

5. What is meant by the term "oscillating neutral"?

6. What is a tertiary winding and when is it used?

7. What are the advantages and disadvantages of each type of connection?

98. The open-delta transformer connection with single-phase transformers. In the open-delta transformer connection three-phase transformation is obtained with two single-phase transformers. Fig. 78 shows the wiring diagram for the open-delta

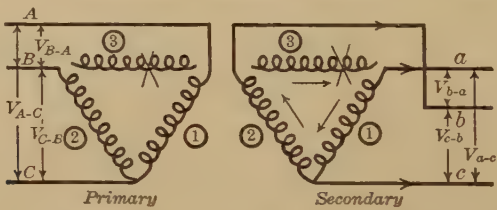

FIG. 78. Open-delta transformer connection

connection. It will be noted that the diagram originally represented a closed-delta connection, but it is assumed that transformer No. 3 has been removed and the remaining two transformers are now connected in open delta. The secondary voltages are the same for both the delta-delta and the open-delta connections. The full-load line currents for the delta-delta bank with a balanced load equal the rated transformer currents multiplied by $\sqrt{3}$. For the open-delta connection the full-load line currents equal the rated transformer currents.

The output of a three-phase system where the load is balanced equals $\sqrt{3} \times V(\text{line}) \times I(\text{line}) \times$ power factor, and is expressed in watts. Therefore, for identical transformers and balanced load

$$\frac{\text{Full-load output, open-delta}}{\text{Full-load output, closed-delta}}$$
$$= \frac{\sqrt{3} \times V\ (\text{line}) \times I_T \times \text{power factor}}{\sqrt{3} \times V\ (\text{line}) \times (I_T \times \sqrt{3}) \times \text{power factor}}$$
$$= \frac{1}{\sqrt{3}} = 0.577,$$

where I_T = rated full-load secondary current of transformer, and V (line) = secondary difference of potential between lines.

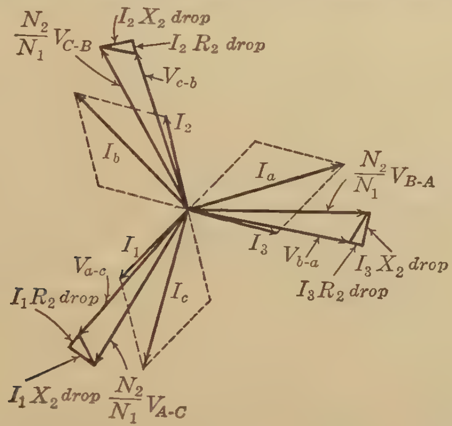

FIG. 79. Delta-delta transformer vector diagram for balanced load

In other words, for balanced load and identical transformers the capacity of the open-delta bank as compared with the delta-delta bank is 57.7 per cent. For example, three 50-kv-a. transformers in closed delta will supply 150 kv-a. Two 75-kv-a. transformers in open delta will supply $(0.577 \times 3 \times 75)$, or 130 kv-a. The full-load output for the open-delta bank with a balanced load is 86.6 per cent of the sum of the two transformer ratings.

The vector diagram for the delta-delta connection with a balanced inductive load is shown in Fig. 79. Identical transformers are assumed.

I_1, I_2, and I_3 = transformer secondary currents,
I_a, I_b, and I_c = secondary line currents,
V_{A-C}, V_{C-B}, and V_{B-A} = primary differences of potential,
$\left(\frac{N_2}{N_1}\right) V_{A-C}$, $\left(\frac{N_2}{N_1}\right) V_{C-B}$, and $\left(\frac{N_2}{N_1}\right) V_{B-A}$ = open-circuit secondary voltages,
V_{a-c}, V_{c-b}, and $V_{b\ a}$ = secondary differences of potential,
R_2 = equivalent resistance (referred to secondary) of each transformer, and
X_2 = equivalent reactance (referred to secondary) of each transformer.

It will be noted that $\bar{I}_a = \bar{I}_3 - \bar{I}_1$,

$$\bar{I}_b = \bar{I}_2 - \bar{I}_3,$$

and

$$\bar{I}_c = \bar{I}_1 - \bar{I}_2.$$

The terminal differences of potential of the secondaries are equal to the open-circuit differences of potential minus (vectorially) the equivalent impedance drops. The vector diagram is symmetrical.

Fig. 80 represents a vector diagram for the open-delta connection. Like transformers that are identical with the transformers considered in Fig. 79 are assumed. The same line currents are assumed in Figs. 79 and 80. Note that $\left(\frac{N_2}{N_1}\right) V_{A-C}$, $\left(\frac{N_2}{N_1}\right) V_{C-B}$, $\left(\frac{N_2}{N_1}\right) V_{B-A}$, I_a, I_b, and I_c are the same in Fig. 79 as in Fig. 80. In Fig. 80,

$$I_2 = I_b,$$

and

$$I_1 = - I_a.$$

When the impedance drops are properly subtracted it will be noted that V_{a-c} is considerably less than $\left(\frac{N_2}{N_1}\right) V_{A-C}$, and that V_{c-b} is very nearly equal to $\left(\frac{N_2}{N_1}\right) V_{C-B}$. Also, $\bar{V}_{b-a} = -(\bar{V}_{a-c} + \bar{V}_{c-b})$ and is so represented.

The vector diagram in Fig. 80 shows that the three secondary differences of potential are somewhat unbalanced under load. The impedance drops are exaggerated so that the voltage unbalance is not as great as the diagram indicates.

When the delta-delta connection is being used and one transformer is damaged, the open-delta connection may be used until

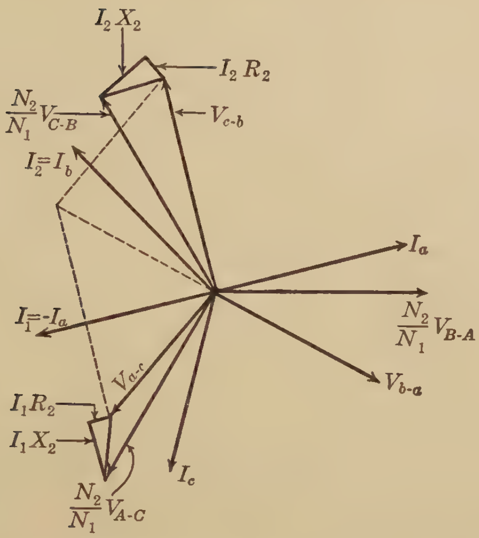

FIG. 80. Open-delta transformer vector diagram for balanced load

the transformer repairs are made; but it must be remembered that the capacity of the two remaining transformers in open delta is 57.7 per cent of the closed-delta bank. The open-delta connection is sometimes used for new installations and a third transformer is added to close the delta when the increase in load warrants the change.

EXPERIMENT 8–N

Transformers connected in Open Delta

Object. To study the voltage regulation of transformers connected in open delta.

Apparatus. Two identical transformers, preferably transformers having high impedance drops so that the change in secondary voltage can be readily observed. A source of three-phase power supply, preferably a Y-connected alternator. Rheostats, inductances, and condensers, or a synchronous motor for loading the transformer bank at different power factors.

Method. Determine the equivalent resistance R_2 and the equivalent reactance X_2 of the transformers. These constants are necessary in order to plot vector diagrams similar to the vector diagram shown in Fig. 80.

Connect the two transformers in open delta and measure the power input to the transformer bank with three wattmeters whose potential coils are connected from line to neutral of the alternator. Measure the power output of each transformer secondary with a suitable wattmeter. Maintain the three primary differences of potential at rated value.

1. Using a balanced noninductive load, vary the load by steps from zero to 150 per cent of rated full-load value. At each step take readings of the line-to-line differences of potential, the line currents, and the power on both sides of the transformer bank.

2. Study the effect of changes in power factor on the regulation of the transformer bank. If a synchronous motor is available as a load, maintain the secondary line currents constant and vary the power factor through as wide limits as possible.

3. Using a single-phase noninductive load connected between lines a and b, Fig. 78, take readings as above. Vary the load between the limits of zero and 150 per cent of rated full load.

4. Using a single-phase load between lines a and b, Fig. 78, and maintaining constant secondary current, vary the secondary power factor through as wide limits as possible and take readings as above.

Curves. For each set of readings plot curves of the three secondary differences of potential as ordinates against the independent variable as abscissas. Also plot curves of the secondary wattmeter readings against the independent variable.

Questions. 1. At what value of power factor do the two secondary wattmeters read alike?

2. A bank of open-delta connected transformers is used to supply several three-phase induction motors. It becomes desirable to supply a few lights from the same transformer bank. How should the lights be connected to the transformers so as to obtain the best voltage regulation on the lighting circuit?

99. Scott connection. The Scott connection is used where it is desirable to change from three-phase to two-phase or vice versa. Two similar single-phase transformers are generally used for this arrangement. Fig. 81 is a diagram which represents the Scott connection where the primary is arranged for three-phase and the secondary will supply two-phase power. One trans-

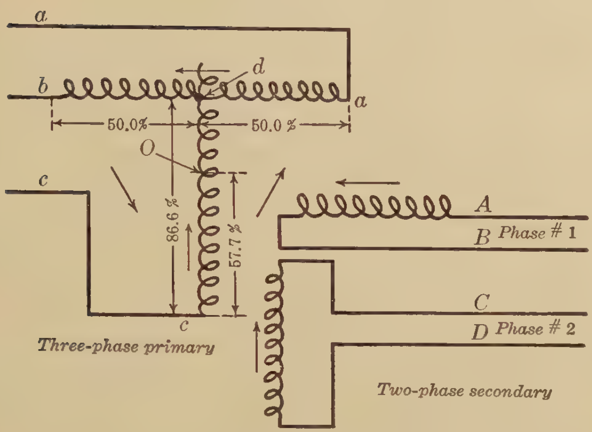

FIG. 81. Scott connection. Three-phase to two-phase

former has a 50 per cent tap. The other transformer has an 86.6 per cent tap and a 57.7 per cent tap if the neutral of the three-phase side is desired. Frequently identical transformers are used and all these taps are available in both. The diagram shows the method of connecting the three-phase side. No taps are needed for the two-phase windings.

Let

N_1 = number of turns on each transformer winding on the three-phase side,

N_2 = number of turns on each transformer winding on the two-phase side,

V_1 = difference of potential between lines on the three-phase side,

V_2 = difference of potential between lines on the two-phase side,

I_1 = line current on the three-phase side,

and I_2 = line current on the two-phase side.

Then, V_2 approximately equals $\left(\frac{N_2}{N_1}\right)V_1$. (The impedance drops are neglected.) If the exciting current and the transformer losses may be neglected, and the load is balanced,

$$\sqrt{3} \times V_1 \times I_1 \times \text{power factor} = 2 \times V_2 \times I_2 \times \text{power factor},$$

and

$$I_2 = 0.866\left(\frac{N_1}{N_2}\right)I_1.$$

The vector diagram for the Scott connection is shown in Fig. 82. Only electromotive force vectors are shown. The electromotive force vectors E_{c-a}, E_{a-b}, and E_{b-c} must be balanced by proper three-phase differences of potential on the primary side (three-phase to two-phase assumed). E_{A-B} is in phase with E_{a-b} and E_{D-C} is in phase with E_{c-d} (E_{A-B} and E_{D-C} are 90 degrees apart).

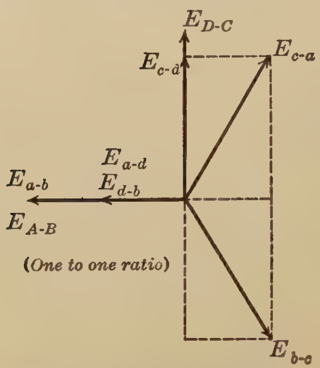

FIG. 82. Vector diagram for Scott connection

When two identical transformers are used with the Scott connection for two-phase to three-phase transformation or vice versa, the full-load output of the combination with a balanced load will be equal to 86.6 per cent of the sum of the two transformer ratings. For balanced loads each transformer will supply approximately half of the load and the secondary terminal voltages will be slightly unbalanced.

EXPERIMENT 8-O

The Scott Connection of Transformers

Object. To study the electrical relations which exist in a bank of Scott-connected transformers.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. XLIII.

Apparatus. Two identical transformers having 86.6 per cent and 50 per cent taps. The 57.7 per cent tap is convenient but not necessary. A three-phase source of power and some means of maintaining constant difference of potential on the primary side of the transformers. Rheostats, inductances, and condensers, or a two-phase synchronous motor, for loading the transformers.

Method. Connect the two transformers as shown in Fig. 81. If the neutral of the power supply or the 57.7 per cent tap on the transformer is available, measure the power input to the transformer bank by the three-wattmeter method, connecting one potential coil terminal of each wattmeter to the neutral.

1. Using a balanced noninductive load, vary the load by steps from zero to 150 per cent of rated load. At each step take readings of current, difference of potential, and power on both sides of the transformer bank.

2. Repeat the above, using a load on one phase only.

3. Repeat, loading the other phase only.

4. Using a balanced load and maintaining the secondary currents constant at rated value, vary the power factor through as wide a range as possible and take readings as before.

5. If a two-phase supply is available, repeat some of the parts, using the two-phase side as the primary and loading the three-phase side.

Curves. Plot curves showing the power delivered per phase to the primary side of the transformer bank under the different conditions of loading. Also plot curves showing the variations in secondary differences of potential for the various conditions of loading.

CHAPTER IX

SYNCHRONOUS MACHINERY

100. Alternator connections. Many of the alternators that are made for electrical-engineering laboratories have twelve armature terminals. These terminals are the ends of six identical

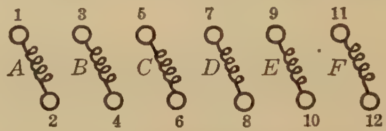

FIG. 83. Laboratory-alternator windings and terminals

windings that are wound so that the electromotive forces generated in adjacent windings have a 30-degree relation. Fig. 83 represents the terminals and windings of such an alternator.

The electromotive forces in windings *A* and *B* are 30 degrees apart. The electromotive forces in windings *B* and *C* are 30

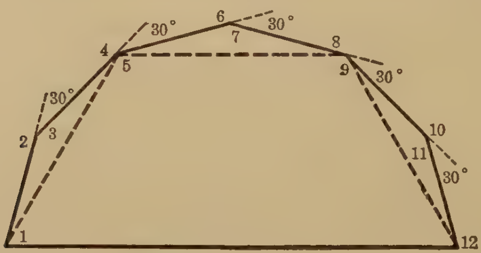

FIG. 84. Vector diagram for a six-winding alternator

degrees apart. The electromotive forces in windings *A* and *C* are 60 degrees apart. The electromotive forces in windings *A* and *F* are 150 degrees apart.

If the individual electromotive forces are known and it is desired to obtain the difference of potential between terminals 1 and 12 with the coils connected in series (connect terminals 2 and 3, 4 and 5, etc.), a vector diagram may be drawn to obtain

the result. (See Fig. 84.) The length of the vector 1–2 represents the electromotive force in winding *A*. The length of the vector

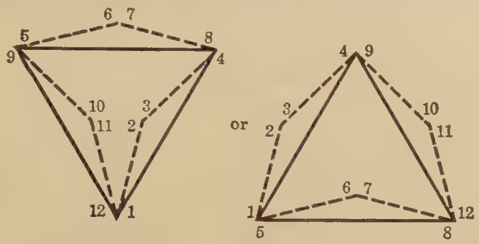

FIG. 85. Vector diagrams for a three-phase, 110-volt delta

3–4 represents the electromotive force in winding *B*. Note that these electromotive forces are 30 degrees apart. The other winding electromotive forces are properly shown. The total

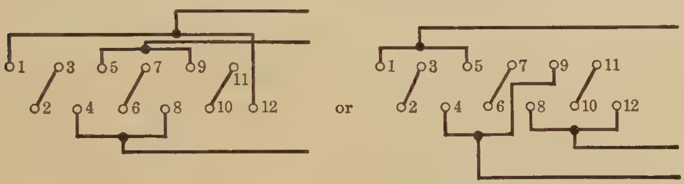

FIG. 86. Terminal connections for a three-phase, 110-volt delta

difference of potential between terminals 1 and 12 is represented by the length of the horizontal line 1–12. If windings *A* and *B* are connected in series, the total electromotive force

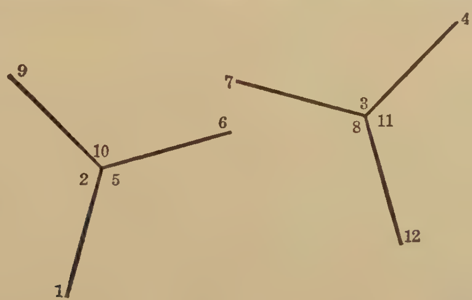

FIG. 87. Vector diagram for a three-phase, 99-volt (line to line) Y

is represented by the straight dotted line 1–4. If windings *E* and *F* are connected in series the total electromotive force is represented by the straight dotted line 9–12.

A six-winding alternator may be used for supplying single-phase, two-phase, three-phase, four-phase, six-phase, and twelve-phase power. Two examples are given below.

EXAMPLES

1. A three-phase, 110-volt, delta connection is desired. Let us assume that the electromotive force per winding is 57 volts. Then if two adjacent windings are connected in series the resultant difference of potential will be 110 volts. The three dotted lines shown in Fig. 84 may be used to form a closed delta as shown in Fig. 85. Correspondingly the terminals would be connected as shown in Fig. 86. There are thirty other possible connections for the three-phase, 110-volt, delta connection.

2. A three-phase, 99-volt (line to line), Y connection is desired. (See Fig. 87.) The vector diagrams shown here are taken from Fig. 84. Correspondingly Fig. 88 shows the two terminal connections. There are other possible terminal connections for the three-phase, 99-volt (line to line), Y connection.

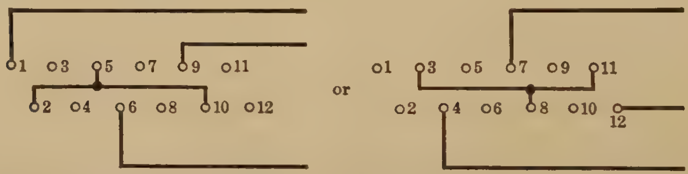

FIG. 88. Terminal connections for a three-phase, 99-volt (line to line) Y

EXPERIMENT 9–A

Connections for a Six-Winding Laboratory Alternator

Object. To study the various connections and the resulting electrical systems which can be obtained from a standard laboratory alternator having six independent armature windings.

Apparatus. A laboratory alternator having six independent armature windings and some means of driving the alternator at constant speed.

Method. Drive the alternator at its rated speed. Adjust the field current of the alternator so as to produce rated voltage. Maintain the speed and the field current constant throughout the test.

1. Take voltmeter readings between the following terminals: 1–2, 3–4, 5–6, 7–8, 9–10, and 11–12.

2. Connect the following terminals: 2 to 3, 4 to 5, 6 to 7, 8 to 9, and 10 to 11. Then take voltmeter readings between the following points: 1–4, 1–6, 1–8, 1–10, 1–12, 3–6, 3–8, 3–10, 3–12, 5–8, 5–10, 5–12, 7–10, 7–12, and 9–12.

3. Construct, graphically, from your readings a figure similar to Fig. 84 (do not assume 30-degree relations).

4. Draw vector diagrams and show terminal connections for the following ways of connecting the alternator. In all vector diagrams draw each vector in the direction established by your diagram in part 3.

Single phase	57 volts,
Single phase	110 volts,
Single phase	220 volts,
Two phase	57 volts,
Two phase	110 volts,
Three phase	57 volts, line to line, delta,
Three phase	110 volts, line to line, delta,
Three phase	99 volts, line to line, Y,
Three phase	191 volts, line to line, Y,
Six phase	57 volts, diametrical,
Six phase	110 volts, diametrical,
Twelve phase	57 volts, diametrical.

The above voltages are based on a normal rating of 57 volts per winding. If the alternator under test has a different voltage rating, the above voltages should be multiplied by the ratio of the rated voltage per winding to 57 volts.

Questions. 1. Wherein does the figure constructed from your readings differ from Fig. 84?

2. What causes this difference?

3. If coils A and C are connected in series, how large a third harmonic can exist in the resultant difference of potential?

101. Magnetization curve of an alternator. The total electromotive force induced in an alternator may be expressed as follows:

$$E = \frac{\sqrt{2}\,\pi k n f \Phi}{10^8} \text{ volts, where}$$

k = a constant which depends upon the arrangement of the turns,

n = number of armature turns in series,
f = frequency in cycles per second, and
Φ = flux per pole.

For a given alternator the above formula reduces to

$E = k'f\Phi$ volts, where
k' is a constant.

Therefore the electromotive force induced in an alternator is directly proportional to $f \times \Phi$, and, if f is held constant, E is proportional to Φ.

The magnetization curve of an alternator may be obtained in the following manner: With the armature terminals open-circuited and the speed held constant, vary the field current I_f. Take readings of E and I_f at regular intervals. A curve plotted between E and I_f will be the magnetization curve.

102. Armature reaction and leakage reactance.* The no-load flux distribution in the air gap of an alternator is symmetrical about the center line of the pole. When current is allowed to flow in the armature windings, a magnetomotive force is produced which combines with the magnetomotive force of the field winding. The resultant magnetomotive force produces a body of flux that usually differs from the no-load flux in magnitude and distribution.

Armature reaction depends upon the value of the armature current as well as the angular relation between the current and the generated electromotive force. Five cases will be considered and a polyphase alternator with a balanced load will be assumed.

Case a. When the armature currents are in phase with the corresponding generated electromotive forces, the resultant armature magnetomotive force resembles the armature magnetomotive force of a loaded d-c. generator. The armature magnetomotive force is at right angles to the field magnetomotive force. As a result there is an increase of flux at one pole tip and a decrease of flux at the other pole tip. The flux per pole Φ is slightly decreased by this distortion.

Case b. When the armature currents are 90 degrees behind the corresponding generated electromotive forces, the resultant magnetomotive force of the armature directly opposes the field

* Practically all laboratory synchronous machines have salient poles and this discussion applies only to that type of machine.

magnetomotive force. There is a corresponding decrease in Φ and there is no distortion.

Case c. When the armature currents are 90 degrees ahead of the corresponding generated electromotive forces, the resultant magnetomotive force of the armature adds to the field magnetomotive force. There is a corresponding increase in Φ and there is no distortion.

Case d. If the armature currents lag behind the corresponding electromotive forces by less than 90 degrees, the resultant armature magnetomotive force may be resolved into two components. One component will be demagnetizing and the other component will be cross-magnetizing.

Case e. If the armature currents lead the corresponding electromotive forces by less than 90 degrees, the resultant armature magnetomotive force may be resolved into two components. One component will be magnetizing and the other will be cross-magnetizing.

Single-phase armature reaction differs from polyphase armature reaction. In polyphase alternators with balanced loads the resultant magnetomotive force of the armature, as well as the flux, remains stationary relative to the field poles. In single-phase alternators the armature magnetomotive force is varying so that there is a double-frequency pulsation of the flux, and a third harmonic in the electromotive-force wave is produced.

The pulsations of field flux in single-phase alternators are damped by the variation in field current which the changing flux produces. In a machine with a comparatively large number of field turns the armature reaction may be considered as practically constant, and may be treated in a manner similar to that used for polyphase alternators.

The leakage reactance of an alternator is practically constant and it depends upon the leakage fluxes about the armature conductors. Some of the leakage flux will be slot leakage flux, and some will be end-connection leakage flux. The slot leakage flux increases with the slot depth and it is inversely proportional to the slot width. It will increase considerably if the slots are partly closed at the top. The end-connection flux follows air paths around the end connections. This component of the leakage flux is comparatively large due to the length of the end connections.

103. Synchronous impedance and synchronous reactance. The synchronous impedance of an alternator is determined by the use of readings taken from the magnetization and short-circuit curves, and it may be expressed as follows:

$Z' = \frac{E'}{I_a}$, where

Z' = syncnronous impedance,

E' = open-circuit electromotive force per phase with field current I_f equal to that value of field current which gives the armature current I_a per phase in the short-circuit test, and

I_a = armature current per phase.

The synchronous reactance X' may be expressed as follows:

$X' = \sqrt{(Z')^2 - (R_a')^2}$, where

R_a' = a-c. armature resistance per phase.

R_a' is usually small so that Z' practically equals X'.

The synchronous reactance is a function of armature-leakage reactance and armature reaction, and it decreases slightly as the field current increases due to the shape of the magnetization curve. It is a fictitious quantity that is useful in graphical constructions. (See § 105.)

EXPERIMENT 9–B

The No-Load Tests of an Alternator

Object. To obtain the magnetization curve and the short-circuit curves of an alternator. To calculate the synchronous impedance of an alternator.

Reference. Christie, "Electrical Engineering," Chap. IX.

Apparatus. The alternator used in Experiment 9-A or some other polyphase alternator. Some means of driving the alternator at different speeds.

Method. 1. Drive the alternator at its rated speed. Vary the field current by steps from zero to 150 per cent of normal value. At each step take readings of the electromotive force in one armature winding, the field current, and the speed of the alternator.

2. Through a suitable ammeter short-circuit one armature winding of the alternator. Make the external impedance as low as possible. Place a dynamometer or soft-iron type of ammeter in the field circuit in series with the galvanometer-type ammeter used in part 1. Vary the field current by steps from zero to such a value as will produce 150 per cent of full-load current in the short-circuited armature winding. At each step take readings of both field ammeters, the armature current, and the speed.

3. Connect two adjacent armature windings in series and short-circuit them through an ammeter. Take a set of readings as in part 2.

4. Connect all six armature windings in series and short-circuit them through an ammeter. Take a set of readings as above.

5. Connect the alternator in delta as shown in Fig. 86. Short-circuit the alternator, placing a suitable ammeter in each line. Take a set of readings as above.

6. With the alternator connected as in part 5, and the field current adjusted to give 150 per cent of full-load armature current, maintain the field current constant and reduce the speed, gradually, to zero. Observe all ammeters as the speed is being reduced.

7. Measure the d-c. resistance of the armature windings. Also measure the resistance of the ammeter and external connections used in each case.

Curves. Plot the magnetization curve and the various short-circuit curves of the alternator. Plot curves of synchronous reactance versus armature current.

Questions. 1. Is the area of the hysteresis loop a measure of the hysteresis loss which is present in the alternator during normal operation?

2. Wherein does the a-c. resistance, R_a', differ from the d-c. resistance, R_a?

3. Why do the readings of the two ammeters in the field circuit of the alternator differ under certain conditions?

4. From a theoretical consideration, what should be the relation between the synchronous impedances as determined for the various armature connections used?

104. Load characteristics. When an alternator is loaded, and the speed and field current are held constant, the terminal difference of potential per phase is influenced by three factors, namely, the I_aR_a' drop, the I_aX_a drop, and armature reaction, where

I_a = armature current per phase,
R_a' = armature a-c. resistance per phase, and
X_a = armature reactance per phase due to leakage flux about conductors.

If the alternator has an inductive load the magnetomotive force of the armature will cause the flux per pole Φ to be reduced. The generated electromotive force will be correspondingly decreased. To obtain the terminal difference of potential it is then necessary to properly subtract the I_aR_a' and I_aX_a drops. The terminal difference of potential of the alternator with the inductive load will be less than the no-load difference of potential.

If the alternator has a condensive load the magnetomotive force of the armature will cause an increase in the flux per pole and a corresponding increase in the generated electromotive force. The I_aR_a' and I_aX_a drops must be properly subtracted to obtain the terminal difference of potential. With a condensive load the terminal difference of potential of the alternator may decrease slightly, remain almost constant, or actually increase as the load is increased. This will depend upon the amount by which the current is leading the alternator electromotive force.

EXPERIMENT 9-C

The Load Tests of an Alternator

Object. To determine experimentally the relations existing between the armature current, load power factor, field current, and terminal difference of potential of an alternator. To determine the regulation of an alternator.

Apparatus. The alternator used in Experiment 9-B and some means of driving it at rated speed. The necessary apparatus for loading the alternator at different power factors.

Method. 1. Drive the alternator at its rated speed. Maintain the terminal difference of potential and the armature cur-

rent constant at their rated values and vary the power factor by steps between as wide limits as possible. At each step take readings of armature current, field current, power output, difference of potential, and speed.

2. Drive the alternator at its rated speed and adjust the field current so as to obtain rated voltage at no load. Maintain the speed and field current constant. Take several sets of readings, holding the armature current constant for each set and varying the power factor between as wide limits as possible. The following values of armature currents are suggested: 25 per cent, 50 per cent, 75 per cent, 100 per cent, 125 per cent, and 150 per cent of full-load current.

3. Drive the alternator at its rated speed and adjust the field current so as to obtain rated difference of potential at full load and unity power factor. Maintain the speed and field current constant and vary the noninductive load from zero to 150 per cent of full load.

4. Repeat part 3, maintaining the power factor constant at 80 per cent lagging.

Curves. 1. Plot a curve, using field current as ordinates and power factor as abscissas.

2. Plot a curve of difference of potential as ordinates and power factor as abscissas for each value of armature current used. Plot curves of difference of potential as ordinates and armature current as abscissas for the following values of power factor: 0 per cent, 50 per cent, 80 per cent, leading, unity, 80 per cent, 50 per cent, and 0 per cent, lagging.

3. Plot the regulation curve for unity power factor.

4. Plot the regulation curve for 80 per cent power factor lagging.

Questions. 1. What is the regulation of this alternator for unity power factor?

2. For 80 per cent power factor lagging?

105. Alternator regulation. The regulation of an alternator may be defined as 100 times the rise in terminal voltage, when the rated kilovolt-ampere load with rated full-load voltage is removed, divided by the rated full-load voltage. It is assumed that the field current and frequency are held constant. The power factor should be specified.

It is usually not practical to obtain the regulation of large alternators by loading the machines, because it is difficult to arrange a large artificial load, the cost of the labor required and the energy consumed is prohibitive, and frequently there is not enough power available for the test.

To avoid loading the alternator in order to determine its regulation, a number of approximate methods have been developed. The necessary tests for these approximate methods require comparatively little power.

Five methods for determining alternator regulation are briefly discussed in the following sections:

§ 106. Synchronous-impedance, or pessimistic, method;
§ 107. Magnetomotive-force, or optimistic, method.

The following three methods are given in the Standards of the American Institute of Electrical Engineers. They are given in the order of preference:

§ 108. By loading;
§ 109. From test curves;
§ 110. From estimated zero-power-factor curves.

The methods given in §§ 106, 107, 109, and 110 are approximate. The method given in § 108 is exact.

106. Synchronous-impedance, or pessimistic, method of determining alternator regulation. The regulation of an alternator is

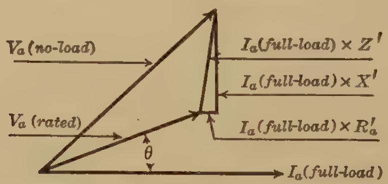

FIG. 89. Synchronous-impedance vector diagram for alternator regulation

determined by the synchronous-impedance method as follows: Draw a vector diagram similar to Fig. 89. The following notation is used in the diagram:

I_a (full-load) = full-load current per phase of the alternator,
V_a (rated) = full-load rated terminal difference of potential per phase,
V_a (no-load) = open-circuit difference of potential,
θ = assumed-load power-factor angle,

X' = alternator synchronous reactance per phase,
Z' = alternator synchronous impedance per phase,
and R'_a = alternator a-c. armature resistance per phase.

The value of X' is determined by the method explained in § 103.

When the synchronous-impedance method is used for determining alternator regulation, the calculated regulation is larger than the true regulation because X' is too large. The method of determining X', as explained in § 103, is for low saturation of the iron and low power factor. The best value of X' to use in determining the regulation is that value which corresponds to the largest field current that can be safely used in the short-circuit test.

107. Magnetomotive-force, or optimistic, method of determining alternator regulation. The alternator regulation by the magnetomotive-force method is determined as follows: Draw a vector diagram similar to Fig. 90. The additional notation is used in this diagram:

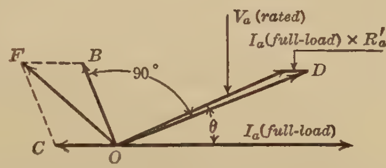

FIG. 90. Magnetomotive-force vector diagram for alternator regulation

OD = vector addition of V_a (rated) and the I_a (full-load) × R'_a drop.

OB = field current necessary to produce an electromotive force numerically equal to OD. OB is taken from the magnetization curve E–I_f. (See § 101.)

OC = field current necessary to produce full-load armature current in the short-circuit test.

OF = vector sum of OB and OC and it represents the total field current necessary to produce the rated full-load difference of potential V_a (rated) at full load.

The no-load difference of potential may be obtained from the magnetization curve. It is that value of generated electromotive force corresponding to a field current equal to OF.

The value of OC used in this method of determining regulation is found with the alternator armature short-circuited and is consequently obtained for low saturation of the iron and low power factor. Due to the low saturation of the iron in the short-circuit test, OC tends to be too short in the vector diagram.

However, the effect of armature reaction in salient-pole alternators is relatively greater at low power factors than at the usual operating power factors; this tends to make OC too long in the vector diagram. These two effects tend to cancel each other.

When the magnetomotive-force method is used for determining regulation, the calculated regulation is usually lower than the true regulation because OC is too short. However, as a general rule the magnetomotive-force method gives better results than the synchronous-impedance method.

108. A. I. E. E. Method No. 1 for determining alternator regulation. This is the direct method for determining the regulation of an alternator. This method is suitable for the determination of regulation for small alternators, and infrequently it may be used for large alternators. The alternator must be loaded at the specified kilovolt-ampere load with rated full-load difference of potential at the armature terminals. The load is then removed and the armature difference of potential measured. It is assumed that the frequency and field current are held constant. The regulation may then be determined. This calculated regulation will correspond to the power factor of the load used when the alternator was loaded.

109. A. I. E. E. Method No. 2 for determining alternator regulation. This method is recommended by the A. I. E. E. when Method No. 1 cannot be used. The magnetization curve and a full-load zero-power-factor curve must be obtained in order to determine the regulation by this method.

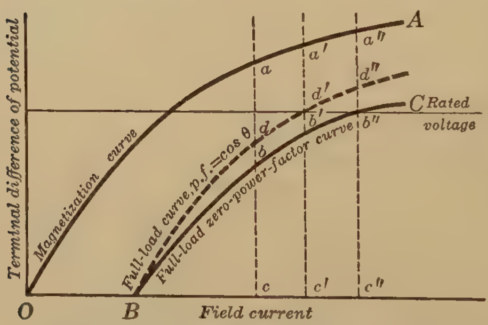

FIG. 91. Curves for determining alternator regulation by A.I.E.E. Method No. 2

The full-load zero-power-factor curve or one approximating very closely to it may be obtained by loading the alternator with a very highly inductive load, and taking a set of readings so that a curve similar to the "Full-load zero-power-factor curve" in Fig. 91 may be plotted. It is suggested

in the A. I. E. E. Standards that the alternator be loaded by means of an idle-running under-excited synchronous motor. The power factor under these conditions is very low and a curve may be obtained that closely approximates the full-load zero-power-factor curve.

The regulation is then determined as follows (see Fig. 91): At any excitation such as *Oc*, the open-circuit difference of potential is *ca*, and the difference of potential at full load with zero power factor is *cb*. The apparent internal drop which is caused by the armature resistance drop, the armature reactance drop, and the effect of armature reaction is represented by *ab*. Therefore the alternator regulation at zero power factor (lagging) equals $\frac{a''b''}{b''c''}$. To determine the alternator regulation for any other power factor it will be necessary to construct vector diagrams similar to Fig. 92.

The vector diagram in Fig. 92 corresponds to the field current *Oc*. (See Fig. 91.) The total internal drop equals *ab*. A line *bf* is drawn which makes an angle θ with the horizontal. This angle θ is the assumed-load power-factor angle. The no-load voltage, *ac*, is swung as a radius about *a*. The arc crosses *bf* at the point *c*. Then *bc* is the terminal difference of potential for the field current *Oc*, full-load armature current, and a power factor equal to $\cos\theta$. The length *bc* is represented as *cd* in Fig. 91. Similar vector diagrams may be drawn for other values of field current, but with the same power factor. It will then be possible to plot a curve similar to the dotted curve (Fig. 91) marked "Full-load curve, p. f. $= \cos\theta$." The alternator regulation for this power factor then equals $\frac{a'd'}{c'd'}$.

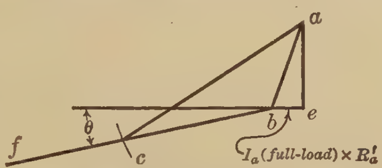

FIG. 92. Vector diagram for determining alternator regulation by A. I. E. E. Method No. 2

The A. I. E. E. Method No. 2 for determining alternator regulation is a modification of the synchronous-impedance method. The method is regarded as empirical, but experience has demonstrated that very good results may be obtained by its use.

110. A. I. E. E. Method No. 3 for determining alternator regulation. This method is recommended by the A. I. E. E. when Methods No. 1 and No. 2 cannot be used. The only difference between Method No. 2 and Method No. 3 is in the manner of obtaining the full-load zero-power-factor curve. In Method No. 3 this curve is estimated.

The full-load zero-power-factor curve may be estimated as follows (see Fig. 93): The line OA is the magnetization curve and OE is the short-circuit curve. The distance OB is the field current that gives full-load armature current in the short-circuit test, and which therefore gives one point on the full-load

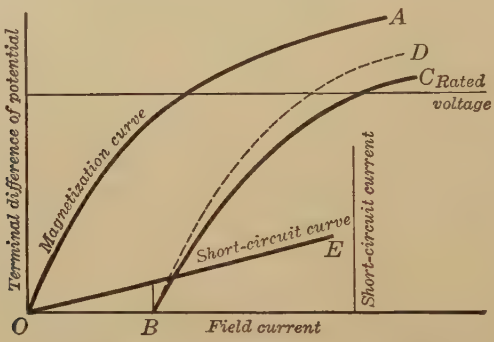

FIG. 93. Curves for determining alternator regulation by A.I.E.E. Method No. 3

zero-power-factor curve. Many turboalternators and high-speed water-wheel alternators are designed with low reactance and low saturation of the iron at normal operation. For this type of machine the full-load zero-power-factor curve may be obtained by shifting the magnetization curve OA horizontally parallel to itself by the distance OB. The resulting full-load zero-power-factor curve will be BD. In many cases the iron is normally well saturated and the reactance is large. The full-load zero-power-factor curve will then deviate from BD to a new position such as BC. The position of BC may be determined with sufficient exactness by investigating the corresponding relation as obtained by test on a machine with similar characteristics and similar magnetic circuit. After the curve BC has been determined, the remainder of the procedure is the same as A.I.E.E. Method No. 2.

EXPERIMENT 9-D

The Regulation of an Alternator

Object. To determine the regulation of an alternator by the various approximate methods, and to compare the results with those obtained by actual loading.

References. A.I.E.E. Standards, No. 7 (July, 1925). Lawrence, "Principles of Alternating-Current Machinery," Chap. V.

Apparatus. The alternator used in Experiment 9-B, and some means of driving it at its rated speed. A synchronous motor for loading the alternator at zero power factor.

Method. 1. Using the data and curves obtained in Experiment 9-B, calculate the regulation of the machine as a three-phase alternator by the synchronous-impedance method for the following values of load power factor: unity, 80 per cent lagging, and 80 per cent leading.

2. Using the data and curves obtained in Experiment 9-B, calculate the regulation of the machine as a three-phase alternator by the magnetomotive-force method for the same values of power factor as used in part 1.

3. With the alternator connected as in Fig. 86 and with the alternator and synchronous motor standing still, connect the two machines electrically. Excite the fields of both the alternator and the synchronous motor to approximately their normal values. Start the alternator and bring it up to its rated speed. This will also start the motor and thereby avoid the necessity of starting the motor by some other means. Reduce the field current of the synchronous motor until the alternator is carrying rated full-load armature current. Maintain the speed and armature current of the alternator constant at their rated values and vary the difference of potential of the alternator from a low value to considerably above the rated voltage of the alternator. Take the necessary readings for plotting a curve similar to the one shown in Fig. 91.

4. Calculate the regulation of the alternator by the A.I.E.E. Method No. 2, for the following values of load power factor: unity, 80 per cent lagging, and 80 per cent leading.

5. Drive the alternator at its rated speed and determine its regulation by the A.I.E.E. Method No. 1, for the same values of power factor as used above.

Question. Which one of the approximate methods gives a result that most nearly agrees with the regulation as obtained by actual loading?

111. Conventional efficiency of a polyphase alternator. The efficiency of an alternator equals

$$\frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{output} + \text{losses}}.$$

This last form of the efficiency expression is most suitable when the slide rule is being used.

The losses (see A.I.E.E. Standards, No. 7 (July, 1925)) may be listed as follows:

1. I^2R losses in the armature and field windings,
2. Friction and windage losses,
3. Core losses,
4. Brush-contact loss,
5. Stray-load losses,
6. Miscellaneous losses.

The I^2R losses in the armature and field windings are based upon the current and measured d-c. resistance, corrected to 75 degrees centigrade.

The best method of determining the field current for a particular load and power factor would be to take the necessary data and then plot curves similar to those in Fig. 91. For the case shown, Oc' is the field current necessary to give the rated difference of potential at full load with a load power factor $\cos\theta$.

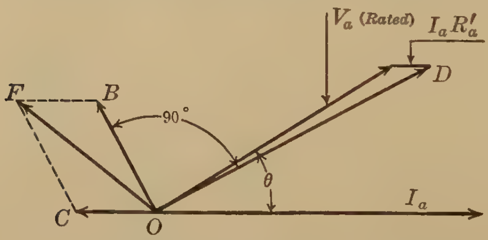

FIG. 94. Magnetomotive-force vector diagram for determining alternator field current

A simpler and easier means of determining field current is the magnetomotive-force method shown in Fig. 94. The following notation is used:

I_a = armature current per phase of the alternator,
R'_a = alternator a-c. armature resistance per phase (the error will be small if the d-c. resistance is used),

θ = assumed-load power-factor angle,

V_a (rated) = full-load rated terminal difference of potential per phase,

OD = vector sum of V_a (rated) and the I_aR_a' drop,

OB = field current necessary to produce an electromotive force numerically equal to OD. The vector OB is taken from the magnetization curve E–I_f (see § 101),

OC = field current necessary to produce the armature current I_a in the short-circuit test, and

OF = vector sum of OB and OC; it represents the total field current necessary to produce the rated difference of potential for the particular load and power factor.

The friction and windage losses may be determined by driving the alternator at its rated speed with a calibrated direct-current motor. The alternator should have its brushes in contact with the slip rings but the field current must be zero. The alternator armature terminals must be open-circuited. If the direct-current motor is directly coupled to the alternator, the output of the motor $(VI_a - I_a^2R_a - 2\,I_a - P_s)$ (see Chapter VI) will represent the alternator friction and windage losses. If the direct-current motor is belted to the alternator, the output of the motor will represent the alternator friction and windage losses plus the belt loss. In this case the belt loss must be estimated and subtracted from the direct-current motor output in order to find the alternator input.

The core losses for a particular load are determined by driving the alternator with the calibrated direct-current motor. The alternator armature terminals must be open-circuited, and the field current of the alternator adjusted to such a value that the difference of potential across the armature will be the rated value plus (vector addition) the IR' drop. Then the output of the calibrated direct-current motor (assuming direct coupling) equals the windage, friction, and core losses of the alternator under test. The core losses of the alternator may be readily determined.

The brush-contact loss is negligible except in the case of revolving armature alternators.

The stray-load losses include additional iron losses due to loading, eddy-current loss in the armature conductors, and additional armature copper loss due to skin effect. These losses are determined by driving the alternator with the calibrated direct-current motor, and operating the alternator with its armature terminals short-circuited and with its field current adjusted to give the desired armature current. The power input to the alternator minus windage, friction, and the calculated I^2R armature loss will give the stray-load losses for a polyphase alternator. This method of determining the stray-load loss is not suitable for single-phase alternators.

The field-rheostat losses and auxiliary-apparatus losses may be considered as miscellaneous losses. All losses due to necessary field rheostats must be included in the determination of efficiency. In the case of direct-connected exciters that are used exclusively for the alternator excitation, the exciter losses must be charged against the alternator.

EXPERIMENT 9-E

The Conventional Efficiency of an Alternator

Object. To determine the various losses in an alternator and from these to determine the conventional efficiency of the alternator.

Reference. A.I.E.E. Standards, No. 7 (July, 1925).

Apparatus. A polyphase alternator and a direct-current shunt motor for driving it. The necessary starting box, field rheostats, etc.

Method. 1. If the driving motor has not been previously calibrated, determine its various losses as outlined in Experiment 6-A so that its mechanical output can be determined for any particular electrical input.

2. Measure the resistance of the field and armature of the alternator. Note the temperature of the machine.

3. Connect the driving motor to the alternator to be tested. Allow the machines to operate for several minutes before taking any readings. With the alternator running at its rated speed, vary the field current of the alternator by steps from zero to the maximum safe value. At each step take readings of field

current, difference of potential, and speed of the alternator, also the armature current, field current, and difference of potential of the driving motor.

4. Short-circuit the alternator armature, placing a suitable ammeter in each line. Drive the alternator at its rated speed and vary the field current by steps from zero to such a value as will produce 150 per cent of the rated full-load armature current in the alternator. At each step take readings of field current, armature current per line, and speed of the alternator, also the armature current, field current, and difference of potential of the driving motor.

Curves. Plot a curve of alternator input (open-circuit test) as ordinates against E as abscissas. Also a curve of alternator input (short-circuit test) as ordinates against the line current as abscissas. Plot a curve of calculated I^2R losses* (internal plus external), at room temperature, plus windage and friction against line current. Plot a curve of load losses against line current. Plot a curve of calculated I^2R losses at 75 degrees centigrade. Plot curves of efficiency as ordinates against kv-a. output as abscissas for power factors of unity and 80 per cent lagging.

Questions. 1. How does this method of determining efficiency compare in accuracy with the efficiency as obtained by loading?

2. For equal armature currents and equal power-factor angles, how do the efficiencies compare for leading and lagging currents?

112. Determination of wave form. Several methods are available for determining wave shape. Two methods are given in this section.

Method No. 1. In this method an oscillograph is used and a photographic picture of the wave is obtained. If a difference-of-potential wave is to be taken, a noninductive resistance must be used to limit the current in the oscillograph vibrator to a safe value. Current waves are taken by shunting one of the oscillograph vibrators across a low noninductive resistance which is in series with the line that is carrying the current. Difference-of-potential and current waves may be shown in their proper phase relation by taking them at the same time.

Method No. 2. In this method the wave form is determined by means of a special contact-maker and the necessary equip-

* See § 126.

ment and instruments. This is known as Mershon's method. A diagram of connections similar to Fig. 95 is used. The contact-maker which is shown in the diagram is connected to the alternator shaft so that as the alternator field (or armature) rotates the contact-maker momentarily makes contact at the same point on the wave each time. It will be noted that the method is essentially a means of balancing a known difference of potential against the unknown instantaneous difference of potential which is supplied from the alternator by way of the contact-maker. The difference of potential V is varied until a noise cannot be heard in the telephone receiver. Then the two differences

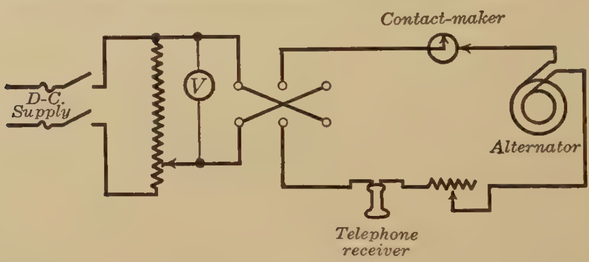

FIG. 95. Mershon's method of determining wave form

of potential are equal, and the voltmeter reading will be the difference of potential for that point on the wave. The contact-maker setting is moved by equal increments over a complete cycle and V is found for each step. It is then possible to plot the wave.

Current waves may be determined by passing the current through a known resistance, and taking the difference-of-potential wave that results across its terminals. The current wave may then be derived from the difference-of-potential wave by the use of Ohm's law.

EXPERIMENT 9–F

The Determination of Wave Form

Object. To determine the wave form of an alternator for different loads and various connections of its armature windings.

References. Swenson and Frankenfield, "Testing of Electro-Magnetic Machinery," Vol. II, Exps. 70, 71, 72, and 73.

Karapetoff, "Experimental Electrical Engineering," Chap. LXIV.

Apparatus. A six-winding alternator such as used in Experiment 9-A. A driving motor. The necessary control apparatus.

Method. This experiment consists of three parts: First, the observation of certain waves on the visual screen of an oscillograph; second, the photographing of certain waves; third, the determination of wave form by Mershon's point-by-point method.

1. Observe the difference-of-potential wave induced in one winding of the alternator. Impress this difference of potential on a condenser and observe the resultant current wave. Impress the difference of potential across an inductance and observe the resultant current wave. Connect windings A and C (Fig. 83) of the alternator in series and observe the resultant difference of potential. Reverse one of the windings and again observe the resultant difference of potential.

2. Photograph such waves as are of particular interest.

3. Determine the form of at least one wave by Mershon's point-by-point method. Place a sufficiently high resistance in series with the telephone receiver (Fig. 95), so as to prevent damaging the telephone receiver by excessive current. As a balance is approached, sensitivity can be improved by reducing the resistance in series with the telephone receiver. Save a copy of the wave thus determined for use in Experiment 9-G.

Questions. 1. Why should the shunt or the multiplier used in connection with an oscillograph element be noninductive?

2. What wave form should you expect when windings A and E (Fig. 83) are connected in series?

113. Wave analysis. Any single-valued periodic function may be expressed by a Fourier series consisting of sine and cosine terms. For example, any irregular periodic difference-of-potential wave may be expressed as follows:

$$v = A_0 + A_1 \sin \alpha + A_2 \sin 2\,\alpha + A_3 \sin 3\,\alpha + \text{etc.}$$
$$+ B_1 \cos \alpha + B_2 \cos 2\,\alpha + B_3 \cos 3\,\alpha + \text{etc.},$$

where

$$\alpha = 2\,\pi f t.$$

The sine and cosine terms are called harmonics and the first harmonics are called fundamental waves.

Alternating current and difference-of-potential waves are symmetrical about the time axis. In other words, they have identical positive and negative loops. In such waves the value of A_0 equals zero and no even harmonics are present. Therefore, for commercial-alternator waves the above equation reduces to

$$v = A_1 \sin \alpha + A_3 \sin 3\,\alpha + A_5 \sin 5\,\alpha + A_7 \sin 7\,\alpha + \text{etc.}$$
$$+ B_1 \cos \alpha + B_3 \cos 3\,\alpha + B_5 \cos 5\,\alpha + B_7 \cos 7\,\alpha + \text{etc.},$$

which may be written as follows:

$$v = C_1 \sin(\alpha + \phi_1) + C_3 \sin 3(\alpha + \phi_3) + C_5 \sin 5(\alpha + \phi_5) + \text{etc.},$$

where $\phi_1 = \theta_1, \quad \phi_3 = \frac{1}{3}\theta_3, \quad \phi_5 = \frac{1}{5}\theta_5, \quad \phi_n = \frac{1}{n}\theta_n,$

and

$$C_1 = \sqrt{A_1^2 + B_1^2}, \qquad \tan\theta_1 = \frac{B_1}{A_1},$$
$$C_3 = \sqrt{A_3^2 + B_3^2}, \qquad \tan\theta_3 = \frac{B_3}{A_3},$$
$$\cdots\cdots\cdots \qquad \cdots\cdots$$
$$C_n = \sqrt{A_n^2 + B_n^2}, \qquad \tan\theta_n = \frac{B_n}{A_n}.$$

Two methods for determining the constants A_1, B_1, A_3, B_3, etc. of an irregular wave are given in the two following articles.

114. Integration method of wave analysis. The coefficients of the Fourier series A_0, A_1, B_1, A_2, B_2, A_3, B_3, etc. may be readily determined for any single-valued periodic function. It may be readily proven that

$$A_0 = \frac{1}{2\,\pi}\int_0^{2\pi} f(\alpha)\,d\alpha,$$

$$A_1 = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\sin\alpha\,d\alpha,$$

$$B_1 = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\cos\alpha\,d\alpha,$$

$$A_2 = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\sin 2\,\alpha\,d\alpha,$$

$$B_2 = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\cos 2\,\alpha\,d\alpha,$$

$$A_3 = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\sin 3\,\alpha\,d\alpha,$$

$$B_3 = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\cos 3\,\alpha d\alpha,$$

$$\cdots\cdots\cdots\cdots$$

$$\cdots\cdots\cdots\cdots$$

$$A_n = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\sin n\alpha d\alpha,$$

$$B_n = \frac{1}{\pi}\int_0^{2\pi} f(\alpha)\cos n\alpha d\alpha.$$

The above integrals cannot be integrated directly because the mathematical equations for $f(\alpha)$ have not been determined.

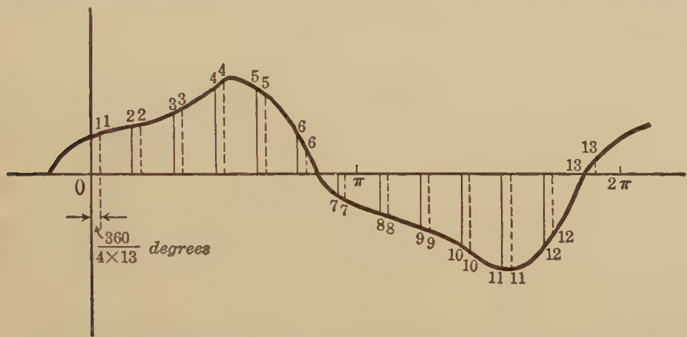

FIG. 96. Irregular alternating current wave for harmonic analysis

Therefore the areas represented by these integrals must be approximated. A planimeter is a very useful instrument for doing this work.

115. Fischer-Hinnen method of wave analysis. The Fischer-Hinnen method is very suitable for analyzing alternating current and difference-of-potential waves.

The process of determining the coefficients of the Fourier series for the waves is as follows: Let Fig. 96 represent an irregular alternating current wave that is to be analyzed, and let it be assumed that all harmonics above the thirteenth are negligible. To determine B_{13}, the distance between 0 and 2π is divided into thirteen parts and an ordinate is drawn for each part. The numbered solid lines in the figure represent the corresponding ordinates. Then B_{13} equals the algebraic sum of the thirteen ordinates divided by thirteen. To determine B_{11}, the distance from 0 to 2π is divided into eleven parts and the

corresponding ordinates are drawn. Then B_{11} equals the algebraic sum of the eleven ordinates divided by eleven. In a similar manner B_9, B_7, and B_5 are determined. If B_9 equals zero, B_3 is determined in the manner described above; but if B_9 is not equal to zero, then the algebraic sum of the three ordinates divided by three will equal $B_3 + B_9$. Thus B_3 can then be readily determined. The length of the ordinate at the origin equals $B_1 + B_3 + B_5 + B_7 + B_9 + B_{11} + B_{13}$, so that B_1 can be determined after all the values of the other B's are known.

We determine A_{13} as follows: Beginning at the first dotted line in the figure, which is $\frac{360}{4 \times 13}$ degrees from the origin, divide the following 2π radians into thirteen parts and construct thirteen ordinates as shown by the dotted lines. Then A_{13} equals the algebraic sum of the thirteen ordinates divided by thirteen. To determine A_{11}, begin at a point $\frac{360}{4 \times 11}$ degrees from the origin and divide the following 2π radians into eleven parts. Draw eleven corresponding ordinates. Then A_{11} equals the algebraic sum of the eleven ordinates divided by eleven. In the same way A_9, A_7, and A_5 are determined. If A_9 equals zero, A_3 is determined in the manner described above; but if A_9 is not equal to zero, then the algebraic sum of the three ordinates divided by three will equal $A_3 - A_9$. Thus A_3 can then be readily determined. The length of the ordinate that is 90 degrees from the origin equals $A_1 - A_3 + A_5 - A_7 + A_9 - A_{11} + A_{13}$. Therefore A_1 can be determined after all the values of the other A's are known.

Usually the harmonics above the thirteenth are negligible, so the process for determining them will not be considered here. A complete and more detailed explanation of this method will be found in Lawrence, "Principles of Alternating Currents," Chap. VI.

EXPERIMENT 9–G

Wave Analysis

Object. To resolve an irregular wave into its component parts.

Reference. Lawrence, "Principles of Alternating Currents," Chap. IV.

Apparatus. No electrical equipment is needed, but use is made of the irregular wave obtained in Experiment 9-F or of a wave supplied by the instructor.

Method. 1. Resolve the irregular wave into its fundamental and harmonics by using the Fischer-Hinnen method. Express the result both in the form

$$e = A_1 \sin \alpha + B_1 \cos \alpha + A_3 \sin 3\,\alpha + B_3 \cos 3\,\alpha + A_5 \sin 5\,\alpha + B_5 \cos 5\,\alpha + \cdots \text{ etc.},$$

and also in the form

$$e = C_1 \sin(\alpha + \phi_1) + C_3 \sin 3(\alpha + \phi_3) + C_5 \sin 5(\alpha + \phi_5) + C_7 \sin 7(\alpha + \phi_7) + \cdots \text{ etc.}$$

2. Check two of the constants obtained in part 1 by the integration method. If a planimeter is available, use it for integrating the areas under the curves.

Curves. Plot, on one curve sheet and to a common scale, the irregular wave, the fundamental, and the harmonics.

Question. If the 27th harmonic were present, how would the process of analyzing the irregular wave be affected?

116. Synchronizing of alternators. In modern power plants several alternators, rather than one alternator, are usually installed. This makes the continuity of service more certain, and better plant efficiency is possible by keeping the running-alternator capacity practically equal to the power-plant output at all times of the day. The capacity of the largest alternator that it is practical to construct is not great enough to supply the power load of the very large stations.

In a power plant it therefore frequently becomes necessary to start an alternator and properly connect it to the station bus bars so that it may supply a part of the station load. The process of paralleling an alternator with another alternator or with several alternators that are already connected to the bus bars is known as "synchronizing."

Low-voltage alternators may be synchronized by simple lamp methods. Fig. 97 shows two lamp methods that may be used for synchronizing single-phase alternators. For synchronizing an alternator, identical small tungsten-filament lamps should be used, due to their low heat storage, in order that the light varia-

tions of each lamp will follow very closely the variation of the difference of potential across its terminals. The voltage rating of the lamps should be at least equal to the bus-bar difference of potential. Better results will be obtained if the maximum difference of potential to which the lamps are subjected in synchronizing is below the rated lamp voltage. If the lamp voltage ratings are equal to the bus-bar voltage, this may be accomplished by placing a third identical lamp in series with the two lamps already shown for each alternator.

In Fig. 97 let it be assumed that the alternator *A* is running and connected to the bus bars. To synchronize alternator *B* with alternator *A*, it is first necessary to have the frequency and voltage of alternator *B* practically equal to the frequency and

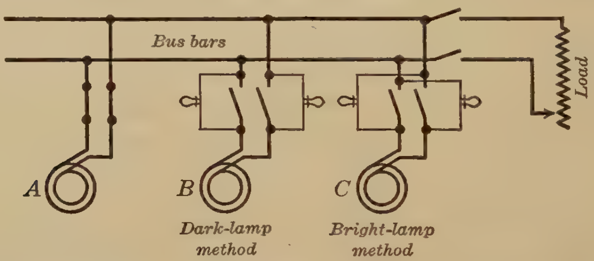

FIG. 97. Connections for synchronizing low-voltage single-phase alternators

voltage of the bus bars. When alternator *B* is so operated, the two lamps will become brightly lighted, then they will become dark, then become bright, then dark, etc. As the frequency of alternator *B* approaches the frequency of alternator *A*, the rapidity of the pulsations decreases. The switch for alternator *B* should be closed at the middle of the dark period, and then alternator *B* will be in parallel with alternator *A*. This method of synchronizing is known as the "dark-lamp" method.

To synchronize alternator *C*, the method differs slightly. When the voltage and frequency of alternator *C* are practically equal to the bus-bar voltage and frequency, the lamps will slowly pulsate in brightness. The switch for alternator *C* should be closed when the lamps are brightest; then the incoming alternator *C* will be in parallel with the other two alternators. This method of synchronizing is known as the "bright-lamp" method.

Figs. 98 and 99 show two diagrams of connections for synchronizing a three-phase alternator. With each connection identical small tungsten-filament lamps should be used. The voltage rating of each lamp should be at least equal to 1.15 times the bus-bar line-to-line voltage, as this will produce normal lamp brilliancy when the lamps are brightest during synchronizing. Better results will be obtained if such lamps may be used that the maximum difference of potential to which they are subjected in synchronizing is below the rated lamp voltage. For example, if in Figs. 98 and 99 the bus-bar differences of potential are 220 volts, each lamp that is represented in the figures may be replaced by three 110-volt lamps and good results in synchronizing will be obtained.

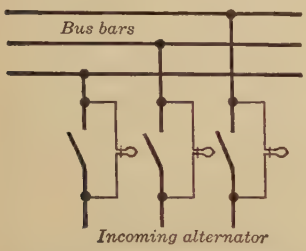

FIG. 98. Dark-lamp method for synchronizing three-phase alternators

In Fig. 98, when the voltage and frequency of the incoming alternator are practically equal to the voltage and frequency of the bus bars, the lamps will all be first bright, then they will all be dark, then they will be bright, then dark, etc., if the phase rotation of the incoming machine is correct. The proper time to close the switch is when the lamps are dark. If the phase rotation is not correct the lamps will not be lighted brightly in unison, and all of them will not be dark at the same time. With this connection the switch should never be closed until the proper phase rotation is established and all the lamps are dark.

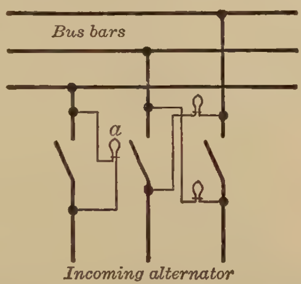

FIG. 99. Three-lamp rotational method for synchronizing three-phase alternators

In Fig. 99, if the phase rotation of the incoming machine is correct the lamps become bright in a definite order while the speed of the incoming machine is too low, and when the speed of the incoming machine is above synchronous speed the lamps become bright in the reverse order. When lamp *a* is dark and the other lamps are equally lighted the switch should be closed.

If the phase rotation of the incoming machine is incorrect all the lamps will be bright and dark in unison. With this connection the switch should never be closed when all the lamps are dark or bright.

For large alternators the lamp methods of synchronizing are not suitable, because the exact time for synchronizing must be known with greater accuracy than these methods give. Instruments known as "synchroscopes" have been designed for synchronizing. These are single-phase instruments and therefore they do not indicate phase rotation for polyphase alternators. For polyphase alternators it is necessary to check phase rotation by some means before the synchroscope is used.

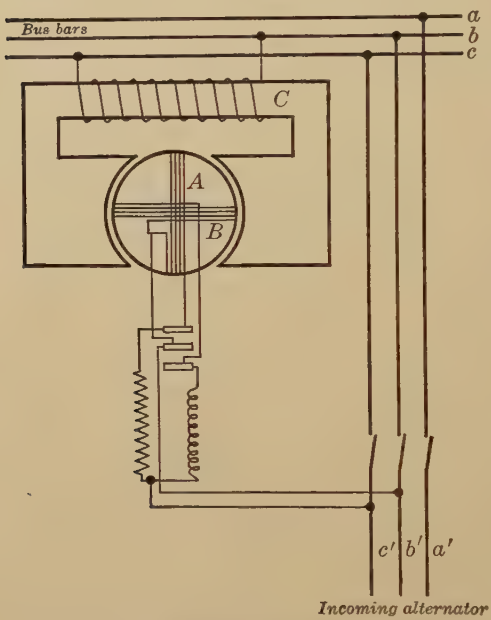

FIG. 100. Dynamometer-type synchroscope

In Fig. 100 are represented the internal connections of a dynamometer-type synchroscope. Coils A and B, which are approximately 90 degrees apart, are wound on a movable laminated iron core. A noninductive resistance is connected in series with coil A, and a highly inductive winding is connected in series with coil B. The coils are then connected to the terminals of the incoming machine. The currents produced in A and B are approximately 90 degrees apart in time relation, and therefore they produce a resultant magnetomotive force that is revolving relative to the movable core. The coil C is on a stationary laminated iron core and its terminals are connected to the two bus bars b and c. The movable coils are attached to the two terminals b' and c' of the incoming machine.

The reaction between the magnetomotive force of the fixed coil and the resultant magnetomotive force of the two coils A and B gives the required torque for turning the movable coils. A pointer is mechanically attached to a shaft that passes through the center of the movable core.

The pointer moving in front of the dial indicates the relative speed and phase position of the incoming machine. The direction of rotation shows whether the speed of the incoming machine is too slow or too fast. When the incoming alternator is running at the right speed and the voltage waves are in phase, the pointer on the synchroscope remains stationary in a vertical position.

117. Parallel operation of alternators. After an alternator has been synchronized with alternators that are already connected to the bus bars, it will be held "in step" by a synchronizing current that flows through the armature circuit and the other alternator armatures. If the alternator tends to advance in phase relative to the other alternators, a synchronizing current is produced which causes the alternator to assume some of the station load and the other alternators are correspondingly relieved of that much of their load. As a result of this synchronizing current, the speed of the alternator is unchanged (transitory conditions neglected). If the driving torque of the prime mover is decreased, the alternator is retarded in phase relative to the other alternators and a synchronizing current flows through the armature circuit and the other alternator armatures. As a result of this synchronizing current, the other alternators assume more of the load and, if necessary, supply power to the alternator, so that there is no change in the alternator speed whatever (transitory conditions neglected).

The proportion of the power-plant load that will be taken by the alternator depends upon the driving torque of its own prime mover. An increase in the driving torque of its own prime mover will cause the alternator to assume more of the load, and a decrease in the driving torque of its own prime mover will cause the alternator to be relieved of part of its load.

At one particular value of field current the power factor of the load supplied by the alternator will be equal to the power factor of the power-plant load. This value of field current is usually desirable. If the field currents of all the alternators are

adjusted in this way, the combined armature copper losses for all the alternators will be a minimum. (It is assumed that each alternator is carrying its proper share of the load.) When a larger field current is used a circulating current is produced in the armature circuit and the other alternator armatures.* This circulating current lags almost 90 degrees behind the generated electromotive force of the alternator, so it produces a magnetomotive force in the alternator armature that is demagnetizing. This current produces magnetizing magnetomotive forces in the other armatures. The result is that the load on the alternator under consideration has been increased by only an extremely small amount and the difference of potential across the bus bars has been increased slightly. Correspondingly, if the field current of the alternator is decreased below the usually desired value, a circulating current is produced that is magnetizing in the alternator under consideration and demagnetizing in all the other alternators. The result is that the alternator under consideration is carrying very nearly as much load as it was originally carrying, and the difference of potential across the bus bars has been decreased slightly. In other words, the load cannot be appreciably shifted from one alternator to the others by changing the alternator field currents. To shift the load from one alternator to the others an appreciable amount, it is necessary to adjust the governor of its prime mover.

EXPERIMENT 9–H

Synchronizing and Parallel Operation of Alternators

Object. To study some of the methods available for synchronizing. To obtain practice in synchronizing. To study the factors influencing the parallel operation of alternators.

Reference. Lawrence, "Principles of Alternating-Current Machinery," Chaps. XXIX to XXXIV, inclusive.

Apparatus. A three-phase alternator and a shunt motor for driving it. The starting box and necessary field rheostats. A source of power supply with which the alternator can be synchronized.

* This circulating current should not be considered as a separate current. It is one of the components into which the armature current may be resolved for the purpose of analysis.

Method. 1. Connect the alternator for synchronizing (single-phase) by the method shown in Fig. 97, *B*. Place an ammeter in the armature circuit. Operate the alternator at its rated speed and adjust the field current so that the difference of potential of the alternator equals the difference of potential of the power supply. Synchronize the alternator by closing the switch when the lamps are dark. Observe the maximum swing of the ammeter when the switch is closed. If the switch is closed at the proper time, the maximum swing of the ammeter should be very small. Each member of the party should practice synchronizing.

2. Place a carbon lamp in parallel with each tungsten lamp. The carbon lamps should be identical and should have about the same candle-power rating as the tungsten lamps. Observe the time lag of the carbon lamps behind the tungsten lamps.

3. Connect the alternator as shown in Fig. 97, *C*, and practice synchronizing.

4. Connect the alternator for synchronizing as shown in Fig. 98, placing an ammeter in one of the leads. Adjust the field current so that the differences of potential of the alternator and the line will be equal. Synchronize and take readings of the maximum deflection and the steady deflection of the ammeter. Reduce the field current by steps, and at each step synchronize and take readings as above. Repeat for field currents greater than normal.

5. Connect the alternator for synchronizing as shown in Fig. 99. Observe conditions above and below synchronous speed and practice synchronizing.

6. Practice synchronizing with a synchroscope.

7. With the alternator connected three phase and operating in parallel with the source of power supply, vary the alternator field current by steps through as wide a range as possible. At each step take readings of current per line, difference of potential line to line, and the power output of the alternator.

8. With the alternator connected as in part 7 and the alternator field current adjusted to normal value, vary the field current of the driving motor by steps between reasonably wide limits. At each step take readings as in part 7.

Precautions. While synchronizing, use a high-range ammeter in the armature circuit so that it will not be damaged by excessive current.

Question. When synchronizing by the lamp method as shown in Fig. 98, how should the voltage rating of the lamps compare with the voltage rating of the alternator?

EXPERIMENT 9-I

The Conventional Efficiency of a Synchronous Motor

Object. To determine the various losses in a synchronous motor and, from these, to determine the conventional efficiency of the motor.

Reference. A. I. E. E. Standards, No. 7 (July, 1925).

Apparatus. A polyphase synchronous motor and a direct-current shunt motor for driving the synchronous motor. The necessary starting box, field rheostats, etc.

Method. This experiment should be performed in the same way as Experiment 9-E. Note that in determining the core losses the IR drop must be subtracted vectorially from the terminal difference of potential instead of being added as in the case of the generator.

Curves. Plot a curve of core loss against E. Also a curve of I^2R plus load losses against line current. Plot curves of efficiency as ordinates against horse-power output as abscissas for power factors of unity and 80 per cent leading.

118. Methods of starting synchronous motors. A synchronous motor may be started and brought up to speed by a sufficiently large direct-current motor. When up to normal speed, the synchronous motor is synchronized with the power supply. (See § 116.) If the synchronous motor has a direct-connected exciter, the synchronous motor may be brought up to speed by using the exciter as a starting motor. A small induction motor is sometimes mounted on the shaft of a synchronous motor for starting purposes. The number of poles on the induction motor is usually two less than the number of poles on the synchronous motor. The speed of the synchronous motor is brought slightly above the synchronous speed by means of the auxiliary induction motor and then the power to the induction motor is shut off. As the synchronous motor slows down it is synchronized with the power supply.

Synchronous motors are usually constructed with amortisseur windings and, consequently, polyphase machines may be started as induction motors. When a polyphase synchronous motor is started in this way and the speed is very nearly up to the synchronous speed, a limited field current should be allowed to flow. The motor will then fall into step and run at synchronous speed. If the synchronous motor has salient poles and it is started as an induction motor, it may reach a speed which is near enough to synchronous speed so that it will pull into step before any field current is allowed to flow. In that event, when the field switch is closed the polarities of the poles may be wrong relative to the armature magnetomotive forces, but the rotating member will slip 180 electrical degrees and then continue to operate at synchronous speed.

If when starting a polyphase synchronous motor as an induction motor the field circuit is left open, the difference of potential across the field terminals will be relatively high. This difference of potential will be a maximum at the instant of starting. The field circuit may be short-circuited during the starting period. This will reduce the insulation stresses and increase the starting torque slightly.

To avoid excessive lagging armature currents in the polyphase synchronous motor when starting it as an induction motor, the difference of potential impressed across its terminals should be considerably less than the rated difference of potential. This reduced voltage may be obtained by a starting compensator which is a specially constructed autotransformer. Starting compensators for synchronous motors are usually constructed with 40, 58, 70, and 85 per cent taps. If the motor is to be started without load the lowest tap gives sufficient torque. Synchronous motors may be started by using reduced-voltage taps on the secondaries of the power transformers.

It is sometimes convenient to start a polyphase synchronous motor with the alternator that is to be used for supplying its power. The alternator and the motor must be standing still until the electrical connections are made. The armatures of the two machines are electrically connected. Both field currents are adjusted to their normal values. When the alternator is started and brought up to speed the synchronous motor will come up to speed with it.

119. V curves of a synchronous motor. The current per phase taken by a synchronous motor equals

$$\bar{I}_a = \frac{\bar{V} + \bar{E}_a}{\bar{Z}'},$$

where $\bar{V}$ = impressed difference of potential per phase,
$\bar{E}_a$ = open-circuit generated electromotive force per phase,
and $\bar{Z}'$ = armature synchronous impedance per phase.

This is represented vectorially in Fig. 101. It will be noted that

$$\bar{E}_0 = \bar{V} + \bar{E}_a,$$

and

$$\bar{I}_a = \frac{\bar{E}_0}{\bar{Z}'}.$$

The armature current I_a lags behind E_0 by an angle equal to

$$\tan^{-1} \frac{X'}{R_a'},$$

where X' = armature synchronous reactance per phase,
and R_a' = a-c. armature resistance per phase.

The power delivered to the motor per phase equals V times I_a times the cosine of the angle between V and I_a. The power delivered to the motor per phase minus the armature copper losses per phase represents the total mechanical power developed per phase within the motor. This equals E_a times I_a times the cosine of the angle between I_a and $-E_a$.

A synchronous motor must run at synchronous speed (neglecting transitory changes). If the external load on the motor is increased, E_a in Fig. 101 will turn slightly clockwise relative to V. Hence E_0 and, correspondingly, I_a will increase. Therefore more power will be supplied to the motor. The motor has been retarded slightly in phase but its speed is unchanged. When the motor is carrying no external load, E_a is very nearly 180 degrees from V, and E_0 and I_a are correspondingly small.

Data may be taken so that curves that are similar to those shown in Fig. 102 may be plotted for a synchronous motor. These curves are called "V curves." Sometimes V curves are plotted with the generated electromotive force per phase instead of field current as abscissas. Each curve corresponds to a particular constant external load on the motor.

The reasons for the shapes of the V curves may be explained by the use of vector diagrams. The diagrams in Fig. 101 represent three values of field excitation for a fixed motor input, and, correspondingly, the horizontal components of I_a are the same in each of the three diagrams. In diagram *A* the motor field current is large, or in other words the motor is over-excited. Note that I_a is large and it is leading V by a large angle. In diagram *B* the motor field current is such that the motor is

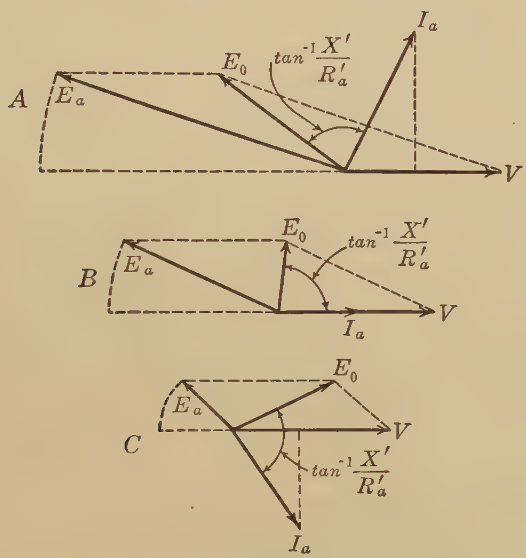

FIG. 101. Vector diagrams for a synchronous motor

drawing an armature current that is in phase with V. In diagram *C* the motor field current is small, or in other words the motor is under-excited. Note that I_a is large and it is lagging behind V.

In Fig. 102 the curves Nos. 1, 2, and 3 are called compounding curves. Curve No. 2 is drawn through points of unity power factor. Curve No. 1 is drawn through points of some particular power factor for lagging armature current. Curve No. 3 is drawn through points of some particular power factor for leading armature current. The shapes of these curves may be readily explained by the use of vector diagrams. The diagrams in Fig. 103 are drawn to represent the conditions for the compounding

curve No. 2. Note that three values of armature current are shown and all of them are in phase with V. This represents unity power factor. If X' and R_a' remain constant, E_0 will follow

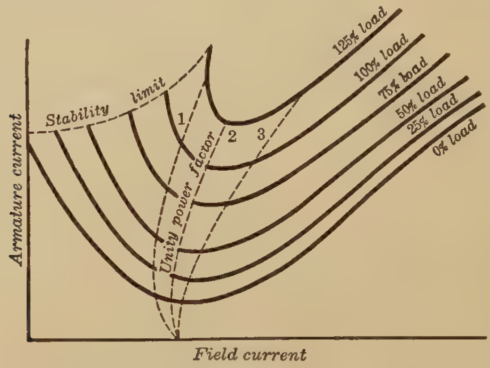

FIG. 102. V curves for a synchronous motor

along the line Ob as the load is increased. At one value of E_0, E_a will be a minimum. This will occur when the line cE_0 is at right angles to the line Ob. For loads above or below the one corresponding to this value of E_0 and I_a, E_a must increase to

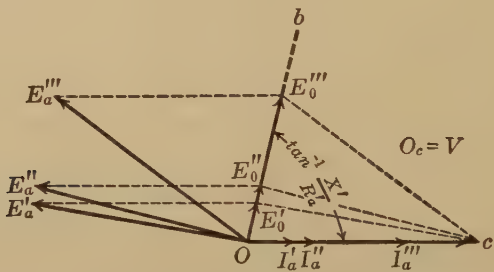

FIG. 103. Vector diagrams for a synchronous motor

maintain unity power factor. This is shown in Fig. 102. As the load increases, curve No. 2 bends toward a lower field current and then increases. The point of minimum field current is well down on the compounding curve and sometimes cannot be reached experimentally.

EXPERIMENT 9–J

The V Curves of a Synchronous Motor

Object. To determine the V curves of a synchronous motor.

Reference. Lawrence, "Principles of Alternating-Current Machinery," Chaps. XXIII and XXIV.

Apparatus. A polyphase synchronous motor and some means of loading it. (A dynamometer is the most convenient means of loading.) The necessary rheostats.

Method. Start the synchronous motor by any suitable and convenient means. With zero external load on the motor, vary the field current by steps through as wide a range as possible. At each step take readings of the difference of potential line to line, the line currents, the power input to the motor, and the field current.

Repeat the above set of readings and, in addition, take the necessary readings for determining the output of the motor, for each of the following values of power output: 25 per cent, 50 per cent, 75 per cent, 100 per cent, and 125 per cent of the rated output of the motor.

Curves. Plot the V curves of the motor. Plot the compounding curves for 80 per cent leading, unity, and 80 per cent lagging power factors.

Questions. 1. For a given value of field current, what is the maximum load which a synchronous motor can carry?

2. What are the structural differences between the synchronous motor and the alternator?

3. How can the hunting of a synchronous motor be reduced?

4. What value of resistance should be used in an amortisseur winding?

EXPERIMENT 9–K

The O Curves of a Synchronous Motor

Object. To determine the O curves of a synchronous motor.

Reference. Magnusson, "Alternating Currents," Chap. XV. McGraw-Hill Book Company, Inc.

Apparatus. The synchronous motor used in Experiment 9-J. The necessary instruments and control apparatus.

Method. Obtain the magnetization curve, the synchronous impedance, and the armature resistance of the synchronous motor. (See Experiment 9-B.) From this data, construct the circle diagram for the motor.

Curves. Using current per line as ordinates and motor excitation in counter volts as abscissas, plot the O curves for the following values of load: 0 per cent, 25 per cent, 50 per cent, 75 per cent, 100 per cent, and 125 per cent of rated full load. Plot the above curves, using field current as abscissas.

Question. How do the O curves obtained from the circle diagram differ from the V curves obtained in Experiment 9-J?

CHAPTER X

INDUCTION MOTORS

120. Starting of polyphase induction motors. Usually the primary windings of a polyphase induction motor are placed on the stator, and the secondary windings are placed on the rotor. The stator, or primary, windings are similar to polyphase alternator armature windings. The rotor may be of the squirrel-cage type or the wound-rotor type. The squirrel-cage type has conductors that are imbedded in the rotor slots. Two rings, one for each end of the rotor, are used for electrically tying the conductors together. The wound-rotor type of induction motor usually has a three-phase winding on the rotor and the three necessary connections to the windings are made accessible by means of slip rings.

A small squirrel-cage induction motor (usually 5 h.p. or less) is usually started by connecting its primary directly to the source of supply. To avoid excessive disturbances in the power system, a relatively large squirrel-cage induction motor is usually started by impressing a difference of potential across the primary (stator winding) that is less than the rated difference of potential. Frequently three fourths of normal voltage is used for starting the motor. After the motor is practically up to speed the rated difference of potential is impressed across the primary. The reduced voltage is sometimes supplied by means of a compensator which is a specially constructed autotransformer, or by means of reduced-voltage taps on the secondaries of the power transformers. The reduced voltage may be obtained by placing impedances in series with the stator windings. Another method of obtaining reduced starting voltage per phase is sometimes used. The motor is designed to be used normally with its stator windings delta-connected. The stator windings are connected in Y and placed across the line for starting. When the motor speed is nearly up to the rated value the stator windings are connected in delta.

Double-squirrel-cage-type induction motors are sometimes constructed. Two independent squirrel-cage windings are used. One winding has a low resistance and the other has a high resistance. The low-resistance winding is placed in the bottom of the rotor slots and the high-resistance winding is placed in the top of the rotor slots. At starting the current in the low-resistance winding is small due to its large leakage reactance. As the motor speeds up and the rotor frequency decreases the rotor winding reactance becomes very small. Therefore the high-resistance winding serves to give the motor a good starting torque and the low-resistance winding serves to reduce the slip and rotor copper losses after the motor is up to speed.

The wound-rotor type of induction motor is usually started by attaching to the rotor terminals a Y-connected starting rheostat. (It is assumed that the rotor has a three-phase winding.) The rated difference of potential is impressed across the primary. The maximum resistances of the rheostat are used at the time of starting. As the motor speeds up the resistances are reduced to zero by steps.

EXPERIMENT 10–A

The Brake Test of a Polyphase Induction Motor

Object. To determine the operating characteristics of a polyphase induction motor by loading it and measuring the input and output.

References. Christie, "Electrical Engineering," Chap. XIII. Magnusson, "Alternating Currents," Chap. XIII.

Apparatus. A polyphase induction motor and a Prony brake or dynamometer for measuring its power output. A suitable source of power supply and some means of maintaining constant difference of potential.

Method. 1. Maintain rated difference of potential at the terminals of the motor and vary the power output by steps from zero to the maximum safe value. At each step take readings of the terminal differences of potential, the line currents, the power input, the weight on the scale, the supply frequency, and the slip.

2. Open one of the supply lines so that the motor will be operating single phase, and take a set of readings as in part 1.

3. Connect the motor as in part 1, but supply it with one half of its rated difference of potential, and take a set of readings as in part 1.

4. Determine the starting torque for each of the three conditions of operation listed above.

Curves. For each of the three sets of readings, plot curves of torque, efficiency, power factor, current, and slip, using horsepower output as abscissas in each case.

Questions. 1. What would be the full-load rating of this motor when operating single phase at rated difference of potential? (Consider both delta-connected and Y-connected primaries.)

2. What would be its rating when operating at one-half normal voltage?

3. What would be the starting torque if 75 per cent of rated difference of potential were impressed on the primary of the motor?

121. Starting of single-phase induction motors. A single-phase induction motor has no starting torque. It must be started by some auxiliary means and it must attain considerable speed before it will develop sufficient torque to overcome its own losses. A single-phase induction motor will run in either direction, and it will continue to run in the direction in which it is started. Several methods of starting single-phase induction motors have been developed. A few of the important methods are briefly described in this article.

Method No. 1. The shading-coil method of starting small single-phase induction fan motors is very common. With this method about one third to one half of each pole is surrounded with a low-resistance short-circuited winding. The action of this short-circuited winding retards the changing of flux in the surrounded portion of the main pole and as a result there is a shifting of the pole flux. This shifting of the pole flux produces a rotating magnetic field that is similar to the rotating magnetic field of the polyphase induction motor. The shading coils are not open-circuited after the motor comes up to speed as the loss incidental to them is negligible. The starting torque that is produced by this method is comparatively small.

Method No. 2. The split-phase method of starting small single-phase induction motors is very common. It is used where

a small starting torque will suffice. In order to use the split-phase method an auxiliary winding is placed on the stator so that it is approximately 90 degrees from the main winding. This auxiliary winding usually has about half as many turns as the main winding and the size of the wire used in the auxiliary winding is much smaller than that of the main winding. As a result the resistances of the two windings are comparable, but the inductance of the auxiliary winding is only about one fourth of that of the main winding. With this arrangement the currents in the coils are considerably out of phase and therefore a rotating magnetic field is produced. After the motor is about up to speed, a centrifugal device that is mounted on the shaft of the motor cuts out the auxiliary winding. This method of starting single-phase induction motors gives a comparatively low starting torque. However, the starting torque for this method is better than that given by the shading-coil method.

In order to use this method of starting single-phase induction motors where comparatively large starting torques are required, a special clutch which is an integral part of the motor is sometimes used. This special clutch slips until the motor is almost up to speed and then it grips and causes the motor to take the load.

Method No. 3. The repulsion-motor method is used for starting single-phase induction motors when large starting torques are required. The advantage of this method is that it gives a high starting torque for bringing the motor up to speed. The starting characteristics are similar to the starting characteristics of a direct-current series motor. The rotor is constructed with a drum-wound armature and commutator that are similar to the armature windings and the commutator of a direct-current motor. The brushes on the commutator are spaced 180 electrical degrees apart and they are electrically tied together so that the armature is short-circuited through the brushes. The position of the brushes relative to the main field winding, which is on the rotor, determines the direction of rotation and the magnitude of the starting current and torque. When the motor is nearly up to full speed, a centrifugal device removes the brushes from the commutator and short-circuits the armature by connecting all the commutator bars together. The motor then operates as a single-phase induction motor.

122. Starting and operating a three-phase induction motor on a single-phase line. It is sometimes convenient to operate a three-phase induction motor on a single-phase line. The diagrams in Figs. 104 and 105 represent two methods for starting and operating a three-phase induction motor on a single-phase line. With the method shown in Fig. 104 the motor will have a greater starting torque than it will have with the method shown in Fig. 105, but the torque per ampere of line current will be

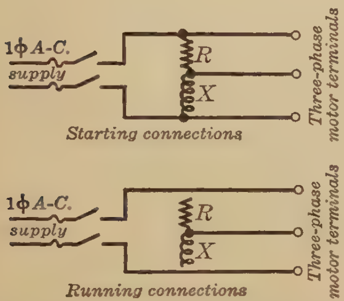

FIG. 104. Method of starting and operating a three-phase induction motor from a single-phase power supply

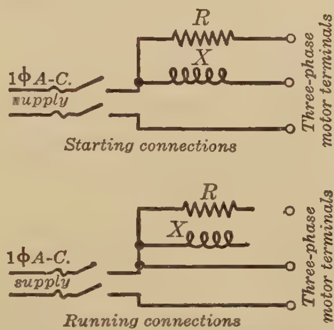

FIG. 105. Method of starting and operating a three-phase induction motor from a single-phase supply

greater for the method shown in Fig. 105. In other words, the method shown in Fig. 105 is more effective than the method shown in Fig. 104. If a condenser of the proper capacity is used to replace the resistor in either Fig. 104 or Fig. 105 the starting torque will be improved, but the first cost of the starting equipment will be increased. The starting torque that may be obtained by the method shown in Fig. 104 or Fig. 105 is comparatively small. A torque of the order of 30 or 40 per cent of full-load torque with two or three times rated current is possible.

EXPERIMENT 10–B

The Brake Test of a Single-Phase Induction Motor

Object. To study the starting and operating characteristics of a single-phase induction motor.

Reference. Lawrence, "Principles of Alternating-Current Machinery," Chaps. LII to LVII.

Apparatus. A single-phase induction motor. A source of power supply and some means of varying the supply difference of potential. A Prony brake or dynamometer for loading the motor.

Method. 1. With the rotor blocked, study the relations between the torque developed, the current required, and the difference of potential supplied to the motor terminals. Starting with a low difference of potential, increase it by steps to the rated value. At each step take readings of difference of potential, current, power input, and the weight on the scale. The heating of the motor is very rapid during the blocked-rotor test. The readings should be taken rapidly and the motor disconnected from the power supply whenever readings are not being taken.

2. Start the motor. Maintain the terminal difference of potential constant at its rated value and vary the load by steps from zero to the maximum torque which the motor will develop. At each step take readings of difference of potential, current, power input, slip, and the weight on the scale.

3. If time and equipment permit, study the effect of changes in the auxiliary starting equipment on the resultant starting torque and starting current.

Curves. Plot curves of starting torque and starting current as ordinates against terminal difference of potential as abscissas. Plot curves of efficiency, power factor, current, torque, and percentage slip as ordinates against horse-power output as abscissas.

Questions. 1. What relation exists between the starting torque and the terminal difference of potential?

2. How do starting torque and starting current at normal difference of potential compare with full-load torque and current?

123. Methods of controlling the speed of a polyphase induction motor. The following outline is given to show the development of speed-control methods somewhat chronologically and commercially, progressing from the more simple to the more complex apparatus. Method No. 1 may be termed the secondary-energy-consumption scheme. Methods Nos. 2, 3, and 4 may be considered as schemes for reducing the value or speed of the rotating magnetic flux, whereas Methods Nos. 5 and 6 may be properly called energy-recovery schemes.

Method No. 1. By resistance units placed in the rotor circuit of a wound-rotor induction motor. This method is recommended when it is necessary to change the speed of the motor occasionally. The efficiency is lowered a great deal as speed is decreased, and the speed regulation of the motor is impaired.

Method No. 2. By varying the difference of potential supplied. The speed of an induction motor may be changed over a small range by variation of the difference of potential supplied to the motor. The principal difficulty encountered is in devising means for varying the difference of potential supplied, without wasting a large amount of energy and impairing regulation. The compensator control gives good results, but it is complicated and expensive, and the coils cannot be short-circuited when a shift is being made from one connection to the next.

Method No. 3. By change of frequency of supply. The chief objection to this scheme is the high first cost of equipment necessary to supply the range of frequency desired.

Method No. 4. By variation of the number of poles. This necessitates regrouping the coils on the stator of a squirrel-cage induction motor so as to alter the number of poles, and thus to alter the synchronous speed of the motor. The first cost of such a motor is high, and the number of speeds available is limited to a small number.

Method No. 5. By cascade connections. If the secondary of a wound rotor is connected to the primary of another induction motor with a short-circuited secondary, and the shafts of the two machines coupled together, the two motors will run at a speed equal to the speed of a motor which has a number of poles equal to the sum or difference of the numbers of poles on the two machines. Thus with two motors there are four possible speeds available.

The chief objection to the cascade connections is the poor utilization of material. The power factor of the combination tends to be low due to the double exciting current in the first motor. The efficiency is very low.

Method No. 6. By commutating devices: a. The Scherbius system of speed control. In this method an electromotive force is introduced into the rotor circuit of the induction motor in order to make the speed changes. If the electromotive force supplied opposes the electromotive force induced in the second-

ary, the speed of the motor will decrease. If the supplied electromotive force is additive to the induced electromotive force of the secondary, the motor speed will increase.

The main induction motor has a wound rotor, and its rotor circuit is connected to brushes on the commutator of a special regulating machine. The armature of the regulating machine is like that of an ordinary d-c. dynamo. The brushes on the commutator are placed 120 electrical degrees apart for a three-phase Scherbius set. The stator of the special regulating machine is very much like the stator of an ordinary polyphase induction motor, and is connected through autotransformers to the rotor of the main motor. The strength of the regulating-machine field is changed by adjusting the autotransformers.

The regulating machine is driven by a separate induction motor, which really acts as a generator when the main motor is operating below synchronous speed, and as a motor when the main motor is driven above synchronous speed.

One difficulty in the above scheme arises when an attempt is made to change the speed of the main motor from a value just below synchronous speed to a speed just above synchronous speed. At the synchronous speed of the induction motor, the excitation of the special regulating machine reduces to zero. Hence, it is impossible to bring the speed of the main motor even up to synchronism without special arrangements. This difficulty is overcome by the use of an "ohmic-drop exciter." The ohmic-drop exciter consists of a frequency changer having an armature like a synchronous converter with a commutator on one end and slip rings on the other. The magnetic circuit is completed by a ring of laminated steel. It is wound for the same number of poles as the main induction motor on whose shaft it is mounted. The rings are connected to the main supply lines through transformers and the brushes on the commutator end, which have 120-degree spacings, are connected to the autotransformers already mentioned for controlling the excitation on the special regulating machine.

The regulating motor is reduced in size for a given speed range if the main motor can be operated above as well as below synchronous speed.

Due to the expense, the Scherbius method of adjusting the speed of an induction motor is limited to large-size installations.

The permissible range of speed is limited by the maximum frequency which can be successfully applied to the regulating machine without excessive commutation difficulties. In general this frequency should not exceed 18 or 20 cycles per second, which corresponds to about a 30 per cent increase or decrease in speed for 60-cycle systems.

b. The Kraemer system of speed control. The Kraemer scheme uses a synchronous converter instead of a special regulating machine for returning a part of the power in the rotor circuit to the system. A synchronous converter is found to give satisfactory operation so long as the slip and the rotor electromotive force of the main motor are great enough to keep the synchronous converter in step. The power appearing on the d-c. side of the synchronous converter may be used for driving a d-c. motor which can be located on the shaft of the main motor, or it may be used for driving a d-c. motor which is attached to a generator that is arranged for supplying power back to the system. The main-motor slip is controlled by changing the field current of the d-c. motor. The power factor of the main motor is controlled by varying the field current of the synchronous converter.

c. The brush-shifting polyphase induction motor. This method is adapted to relatively small units and is less complicated than the Scherbius or Kraemer method of adjusting the speed of an induction motor. The primary winding is placed on the rotor and the secondary winding is placed on the stator. (See Fig. 106.) The rotor has another winding, which is called the regulating winding. This regulating winding is a simple d-c. armature winding which is provided with a commutator. The function of the commutator is to change the frequency developed in the regulating winding (which is the frequency of the power supply) to the frequency of the stator winding which is the secondary.

The primary winding and the regulating winding are placed in the same slots on the rotor, and therefore the electromotive force induced per turn is the same in both windings. The difference of potential between any two brushes that are riding on the commutator will depend upon the turns included between the two parts of the commutator upon which the brushes are located. The maximum difference of potential between brushes

will be obtained when the brushes are so set that they are 180 electrical degrees apart.

It will be noted in Fig. 106 that a brush is connected to each of the two ends of one phase of the secondary which is on the stator. If the two brushes happen to be located on the same commutator segment, the secondary winding will be short-circuited; with this position of the brushes the machine would operate as an ordinary induction motor. However, if the brushes are separated

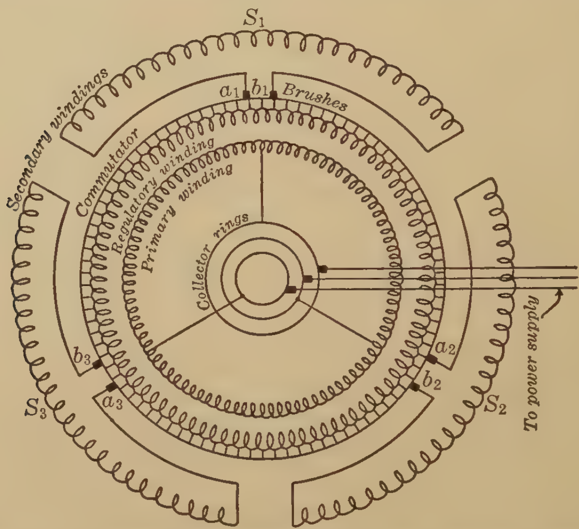

FIG. 106. Diagrammatic sketch of the brush-shifting polyphase induction motor

on the commutator, an electromotive force with secondary frequency will be inserted into the secondary circuit. It will also be noted in Fig. 106 that all of the secondary phases are independent. Therefore it is necessary to have brushes for each phase. These brushes are properly located on two brush yokes that are arranged so that they may be shifted in opposite directions. A hand wheel, the necessary gears, and yoke teeth are arranged so that the yokes may be moved in opposite directions easily.

The motor will operate above as well as below synchronous speed.

EXPERIMENT 10–C

Speed Control of a Polyphase Induction Motor

Object. To study some of the methods available for controlling the speed of a polyphase induction motor.

Reference. Karapetoff, "Experimental Electrical Engineering," Chaps. XXII, LV, and LVIII.

Apparatus. A polyphase wound-rotor induction motor. A power supply whose frequency and difference of potential can be varied. A suitable rheostat for use in the rotor circuit of the induction motor. A Prony brake or dynamometer for loading the motor.

Method. 1. Study the effect of varying the supply difference of potential. Operate the motor at full-load torque and rated frequency. Vary the supply difference of potential by steps from 75 per cent to 125 per cent of rated value. At each step take readings of the terminal differences of potential, stator currents, rotor currents, power input, frequency, slip, and the weight on the scale.

2. Study the effect of varying the frequency of the power supply. Maintain the torque of the motor constant at full-load value. Also maintain normal flux density (the ratio $\frac{E}{f}$ constant at normal value). Vary the frequency by steps through as wide a range as possible. At each step take readings as in part 1.

3. Study the effect of varying the resistances in the rotor circuit. Operate the motor at rated difference of potential, rated frequency, and full-load torque. Vary the resistances in the rotor circuit by steps from zero to the maximum possible value. At each step take readings as in part 1.

4. Study the speed regulation of the motor when resistance is inserted in the rotor circuit. Operate the motor at rated frequency and difference of potential. Maintain the resistance of the rotor circuit constant at such a value as will give approximately one-half synchronous speed at full-load torque. Vary the torque of the motor by steps from zero to 150 per cent of full-load value. At each step take readings as in part 1.

Curves. In each case plot the necessary curves to illustrate your results.

Questions. 1. When controlling speed by inserting resistance in the rotor circuit, what is the maximum efficiency attainable at one-half synchronous speed?

2. How do the various methods of speed control for induction motors compare in regard to efficiency?

3. In regard to first cost of equipment?

124. Running-light test of an induction motor. The core loss plus the friction and windage losses of an induction motor may be readily determined by the running-light test, and if sufficient data are taken during the running-light test the friction and windage losses may be separated from the core loss.

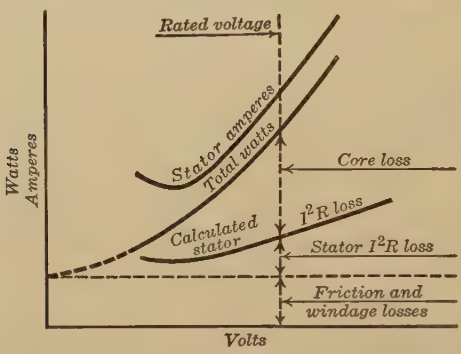

FIG. 107. Running-light curves for an induction motor

In the running-light test the motor is run without load. In order to be able to separate the friction and windage losses from the running-light losses, the difference of potential across the stator terminals is varied from about 25 per cent above the rated value down to the lowest value that will keep the motor running. The rated frequency is used during all of the test. Readings are taken so that curves similar to the "total-watts" and "stator-amperes" curves shown in Fig. 107 can be plotted. Then the friction loss of the motor may be determined by extending the total-watts curve to the watts axis. The ordinate at the point of intersection equals the motor friction and windage losses. The rotor copper loss may usually be neglected in the running-light test. The stator copper loss may be readily calculated if the stator resistance is known (see § 126 for three-phase motor), and a curve similar to the "calculated-stator-I^2R-loss" curve may be drawn. This curve is drawn so that for any particular voltage the length of the ordinate between the curve and the "friction-and-windage" line equals the stator I^2R loss. Then the length of any ordinate between the total-watts curve and

the calculated-stator-I^2R-loss curve represents the motor core loss for the corresponding difference of potential considered.

125. The locked-rotor test of an induction motor. In this test the rotor is locked and the difference of potential across the

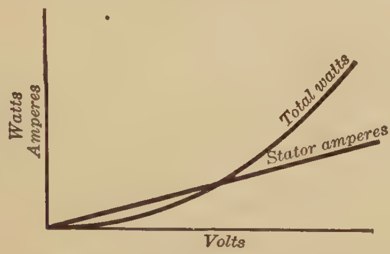

FIG. 108. Locked-rotor curves for an induction motor

stator terminals is varied from a low value up to that value which will give a reasonably large stator current. Readings are taken so that curves similar to those shown in Fig. 108 may be drawn. The "stator-amperes" curve is practically a straight line. The power input to the motor is made up of stator and rotor copper losses plus a very small core loss. Usually this small core loss may be neglected. The stator I^2R loss may be

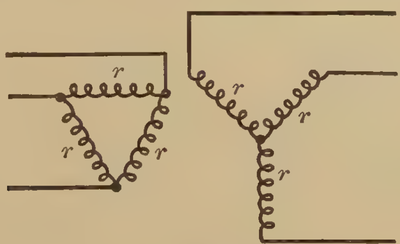

FIG. 109. Three-phase windings

calculated (see § 126 for three-phase motor) and a "stator-I^2R-loss" curve plotted. Then for any particular stator current the rotor I^2R loss will be represented by the difference in the lengths of the two ordinates for the two copper-loss curves. The rotor I^2R loss of a wound rotor may be readily calculated if the rotor resistance is known (see § 126).

126. Copper loss in any three-phase winding. Consider the delta and Y windings shown in Fig. 109.

Let $r =$ the resistance per phase for both windings.

Then the measured resistance between any two line terminals for the delta winding is

$$R = \frac{1}{\frac{1}{r} + \frac{1}{2r}} = \frac{2r^2}{3r} = \frac{2}{3}r.$$

For balanced currents the copper loss in the delta winding equals $3(I_{\text{per phase}})^2 r$, but I_{line} equals $\sqrt{3}\, I_{\text{per phase}}$ and, therefore, the copper loss equals $\frac{3}{2} I_{\text{line}}^2 R$.

The measured resistance between any two terminals of the Y connection is

$$R = 2r.$$

For balanced currents the copper loss in the Y winding equals $3(I_{\text{per phase}})^2 r$, but I_{line} equals $I_{\text{per phase}}$ and, therefore, the copper loss equals $\frac{3}{2} I_{\text{line}}^2 R$.

In other words, for a delta or Y winding the copper loss for balanced currents equals $\frac{3}{2} I_{\text{line}}^2 R$,

where $R =$ resistance between any two terminals of the three-phase winding.

EXPERIMENT 10-D

The No-Load Tests of a Polyphase Induction Motor

Object. To determine the core loss and friction and windage losses of a polyphase induction motor by the running-light test. To determine the copper loss of a polyphase induction motor by the locked-rotor test.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. LII.

Apparatus. A polyphase induction motor, preferably the same motor as used in Experiment 10-A. A power supply whose difference of potential can be varied between wide limits. Some means of locking the rotor of the induction motor.

Method. 1. With the motor running without load, vary the supply difference of potential by steps from 125 per cent of rated value to as low a value as will keep the motor rotating. At each step take readings of the differences of potential, stator currents, and power input.

2. Lock the rotor so that it cannot rotate. Vary the difference of potential impressed on the stator by steps from a low value to as high a value as can be used without the resulting current overheating the motor. At each step take readings as in part 1.

3. Investigate the variations in starting torque with changes in the angular position of the rotor. Take several readings of static torque for constant stator difference of potential, changing the angular position of the rotor slightly after each reading. The change in starting torque with change in position of the rotor is particularly large for wound-rotor induction motors.

4. Measure the resistance of the stator and also the rotor if the motor is of the wound-rotor type.

Curves. 1. Plot curves similar to those shown in Fig. 107. 2. Plot curves similar to those shown in Fig. 108. 3. Plot a curve of starting torque against angular position of the rotor.

Questions. 1. What per cent of full-load input is used in overcoming friction and windage losses?

2. Core loss?

3. Stator copper loss?

4. Rotor copper loss?

127. The circle diagram of an induction motor. An equivalent circuit for an induction motor is shown in Fig. 110. In this

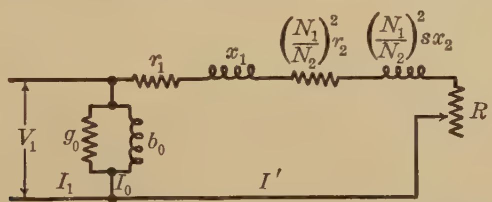

FIG. 110. Equivalent circuit for an induction motor

diagram the following notation is used:

r_1 = stator a-c. resistance per phase,
r_2 = rotor a-c. resistance per phase,
x_1 = stator leakage reactance per phase,
x_2 = rotor standstill leakage reactance per phase,

$$s = \text{slip} = \frac{\text{synchronous speed} - \text{actual speed}}{\text{synchronous speed}},$$

N_1 = stator turns per phase,

N_2 = rotor turns per phase,
g_0 = the conductance of a path to accommodate the power component of the exciting current,
b_0 = the susceptance of a path to accommodate the magnetizing component of the exciting current,
V_1 = impressed difference of potential per phase,
I_1 = stator current per phase,
I' = load component of the stator current per phase,
I_0 = exciting current per phase (this is the running-light current per phase), and
R = a load resistance in the equivalent circuit that will consume the same amount of power as the mechanical load of the motor consumes per phase.

The equivalent circuit shown in Fig. 110 may be modified as shown in Fig. 111; the errors that will result from this change

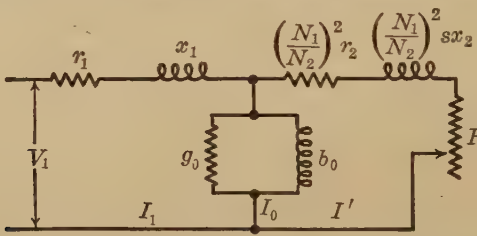

FIG. 111. Approximate equivalent circuit for an induction motor

will be very small. The approximate equivalent circuit shown in Fig. 111 is very convenient for the development of the induction-motor circle diagram.

The secondary reactance sx_2 is proportional to the rotor frequency and therefore varies with the load on the motor. However, under the usual operating conditions sx_2 is very small, so that for the purpose of constructing the circle diagram it may be assumed that $x_1 + \left(\frac{N_1}{N_2}\right)^2 sx_2$ is practically constant. A change in the load on the induction motor is equivalent to a change of R in the equivalent circuits shown in Figs. 110 and 111. An induction motor with a variable load may then be represented as a circuit having a constant reactance and a variable resistance in series (see Fig. 111), and therefore the locus for I' is a circle. (See Magnusson, "Alternating Currents," Chap. VI.)

The circle diagram for an induction motor is constructed as follows: In Fig. 112, V_1 represents the difference of potential per phase. A suitable current scale is selected for all current vectors. The line Of represents the exciting current per phase and is drawn so that it makes an angle with OV_1 equal to the angle of lag between the current and voltage in the running-light test. The line Os represents the stator current per phase for the locked-rotor test with rated difference of potential impressed, and the angle between Os and OV_1 must be equal to the angle of lag between the current and voltage in the locked-rotor test. A horizontal line is drawn from the point f to the

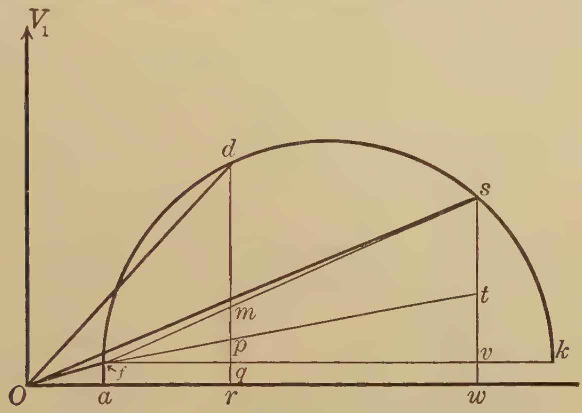

FIG. 112. Circle diagram for an induction motor

right. Then a semicircle is constructed so that it passes through the points f and s and the center of the semicircle is on the horizontal line that was drawn from the point f to the right.

The vector Od represents the stator current per phase for some particular load. As before, Of represents the exciting current. A line drawn from f to d (not shown) would represent the load component of the stator current.

The product of V_1 and Of represents the friction, windage, and core losses (per phase) plus a very small copper loss. When the motor is running with no load, the friction, windage, and stator core loss are a maximum, and the rotor core loss is a minimum. As the motor is loaded, the friction, windage, and stator core loss decrease slightly and the rotor core loss increases. At standstill the friction and windage losses are absent

and the stator core loss has decreased considerably, but the rotor core loss is now comparable with the stator core loss. Therefore, it is assumed that the sum of the friction, windage, stator core loss, and rotor core loss is practically constant.

The copper losses per phase at standstill are nearly equal to V_1 times sv. The line sv may be divided so that V_1 times st equals the rotor copper loss, and V_1 times tv equals the stator copper loss. For squirrel-cage induction motors tv may be readily determined and the remainder st when multiplied by V_1 will represent the rotor copper loss. A line ft is then drawn.

For any stator current Od, the following relations are true if n equals the number of phases:

$$nV_1qr = \text{friction, windage, and core losses},$$

$$nV_1pq = \text{stator copper loss},$$

$$nV_1mp = \text{rotor copper loss},$$

$$nV_1dm = \text{motor output},$$

$$nV_1dr = \text{motor input},$$

$$\frac{dm}{dr} = \text{motor efficiency},$$

$$\frac{dr}{Od} = \text{motor power factor},$$

and

$$\frac{mp}{dp} = \text{slip, } s.$$

The torque developed at the pulley equals

$$\frac{nV_1dm}{746} \times \frac{33{,}000}{2\,\pi N} \text{ pound-feet},$$

where N = actual speed of the rotor in revolutions per minute.

The maximum possible output of an induction motor may be determined by the method shown in Fig. 113. A line is drawn parallel to fs and tangent to the circle. The point of tangency is labeled d'. The maximum possible output of the motor will be equal to

$$nV_1d'm'.$$

The maximum possible torque of an induction motor may be determined by the method shown in Fig. 113. A line is drawn parallel to ft and tangent to the circle. The point of tangency is labeled d''. The maximum possible torque will be

$$\frac{nV_1d''m''}{746} \times \frac{33{,}000}{2\,\pi N} \text{ pound-feet}.$$

Fig. 114 shows methods of construction so that the percentage power factor, efficiency, and slip may be read directly. The power-factor quadrant is drawn with any convenient radius.

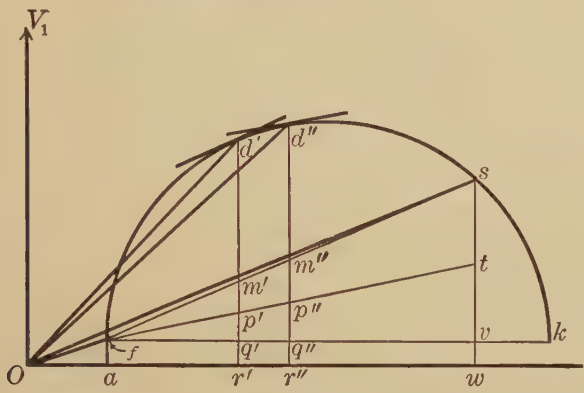

FIG. 113. Determination of maximum output and maximum torque from the circle diagram

The vertical radius is scaled as shown. Where the stator current Od cuts the quadrant at y, a line is projected to the scaled axis and the power factor is read directly from this scale.

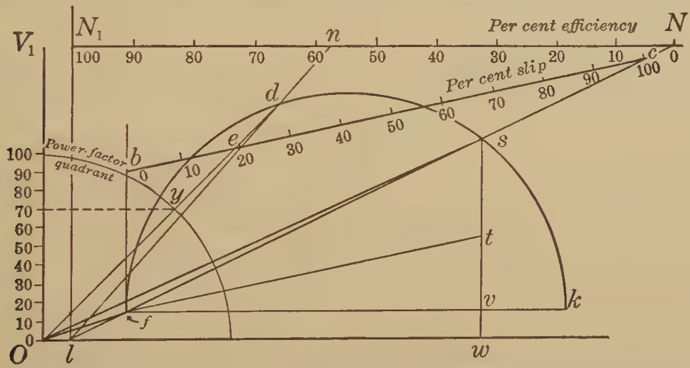

FIG. 114. Determination of power factor, efficiency, and slip from the circle diagram

The per-cent-efficiency scale is constructed as follows: Extend the line fs to l and construct a vertical line through l. Draw any suitable horizontal line that intersects the vertical line drawn through l and the extended line fs, as shown. The line

N_1N is scaled with zero-per-cent efficiency at the point N and 100-per-cent efficiency at the point N_1. Where the line ld (extended if necessary) cuts N_1N at n, the efficiency may be read directly.

The per-cent-slip scale is constructed as follows: Draw a vertical line fb. Then draw any suitable line so that it is parallel to ft and intersects the line fb and the extended line fs. The points of intersection are labeled b and c in the figure. The line bc is then scaled with zero-per-cent slip at the point b and 100-per-cent slip at the point c. Where the stator current Od (extended if necessary) cuts bc at the point e, the percentage slip may be read directly.

For the stator current Od, the power factor is about 71 per cent, the efficiency is about 58.5 per cent, and the slip is about 18.5 per cent.

EXPERIMENT 10-E

The Circle Diagram of an Induction Motor

Object. To construct the circle diagram of a polyphase induction motor from data obtained by no-load tests.

Reference. Christie, "Electrical Engineering," Chap. XIII.

Apparatus. No electrical apparatus is needed if Experiment 10-D has been performed.

Method. Construct the circle diagram of the induction motor from the data obtained in Experiment 10-D. If the rated difference of potential was not reached in the locked-rotor test, the value of current and power factor at rated difference of potential may be obtained by extrapolation. From this circle diagram determine the various operating characteristics of the motor.

Curves. Plot the following performance curves of the motor by scaling the values from the circle diagram: efficiency, power factor, stator current, torque, and slip as ordinates against horse-power output as abscissas.

Questions. 1. What assumptions are made in the construction of the circle diagram?

2. How do the performance curves obtained from the circle diagram compare with those obtained in Experiment 10-A?

3. What could be done to improve the accuracy of the data obtained from the circle diagram?

128. The induction generator. Under certain conditions an induction motor may be operated as an induction generator. In order to make an induction motor act as an induction generator, it must be driven above synchronous speed and it must be operating in parallel with a synchronous generator. Under these conditions the output of the induction generator may be increased only by increasing the speed at which it is driven, and the power factor of that portion of the load supplied by the induction generator will depend entirely upon the induction

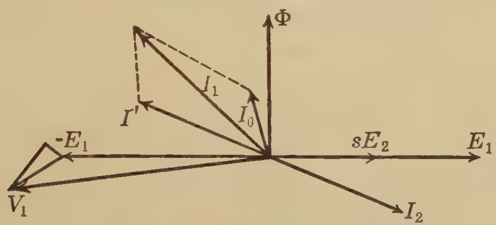

FIG. 115. Vector diagram for an induction motor operating below synchronous speed

machine's own constants. The voltage and frequency of the system will depend upon the voltage and frequency of the synchronous generator.

A vector diagram for an induction machine operating below synchronous speed (the machine is operating as a motor) is shown in Fig. 115. The following notation is used:

Φ = mutual flux,
sE_2 = slip electromotive force induced in the rotor circuit,
E_1 = electromotive force induced in the stator winding,
I_2 = rotor current,
I' = load component of the stator current,
I_0 = exciting current,
I_1 = total stator current, and
V_1 = stator terminal difference of potential.

A vector diagram for an induction machine operating above synchronous speed (the machine is operating as an induction generator) is shown in Fig. 116. The numeric values of the slip are the same for the two cases (Figs. 115 and 116) but they are of opposite signs. Due to the negative slip, it will be noted that I_2 leads sE_2 in Fig. 116. It will also be noted in this figure

that I_1 (the current that is being supplied to the load) is leading V_1. The current that is supplied by an induction generator will always be leading.

An induction generator cannot supply lagging current to a load and therefore the synchronous machines in parallel with it must have sufficient capacity to supply the lagging component of the load current as well as the quadrature component of the induction generator.

In a few electrical railway installations in mountainous sections, induction motors are used on the locomotives. When the train tends to accelerate after a certain speed has been reached

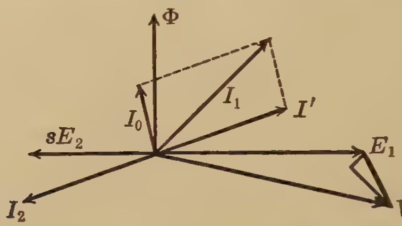

FIG. 116. Vector diagram for an induction motor operating above synchronous speed. (Induction generator)

on a down grade the induction motors become induction generators, and power is delivered to the electrical system. This gives considerable safety of operation and the brake-shoe maintenance is reduced a great deal.

For experimental purposes an induction generator may be used independently if loaded with a condensive load.

EXPERIMENT 10–F

The Load Test of an Induction Generator

Object. To study the operating characteristics of an induction generator.

Reference. Lawrence, "Principles of Alternating-Current Machinery," Chap. L.

Apparatus. An induction motor to be used as an induction generator. Some means of mechanically driving the induction machine above its synchronous speed. A dynamometer should be used, if possible, so that the mechanical input to the

induction generator can be measured. A suitable source of power supply. Static condensers.

Method. 1. Start the induction machine as a motor from the power supply. Leave the induction machine connected to the a-c. power supply and increase the mechanical power input to the induction machine by steps. At each step take readings of the difference of potential, frequency, current, and power output of the induction generator.

2. Connect static condensers of suitable capacity to the stator of the induction generator. Discount the a-c. supply line and load the generator with a resistance load. Maintain the speed constant and vary the resistance load by steps. At each step take readings of the terminal difference of potential, current delivered by the induction generator, current taken by the static condensers, current taken by the resistance load, the power output, speed, and frequency of the induction generator.

3. Study the effect of changing the capacity of the condensers used in part 2.

Curves. Plot the necessary curves to illustrate your results.

Question. What are the relative advantages and disadvantages of the induction generator?

CHAPTER XI

CONVERTERS

129. Introduction. This chapter deals more particularly with the following kinds of converters:

1. A-c. to d-c. or d-c. to a-c. converters.
   a. Synchronous converters;
   b. Mercury-vapor-arc rectifier.
2. Frequency converters.
   a. Induction type.
3. Phase converters.
   a. Polyphase-induction-motor method.

130. Starting of synchronous converters. A synchronous converter may be started by either of the following methods:

1. By starting the synchronous converter as an induction motor from the a-c. side. This method applies only to polyphase synchronous converters. (See § 118.)
2. By starting the synchronous converter from the d-c. side.

Method 1. Synchronous converters usually have amortisseur windings and therefore polyphase synchronous converters may be started as induction motors from the a-c. side. About one-third to one-half normal difference of potential is used during the starting period. The shunt field is frequently arranged so that it may be opened in several places by means of a sectionalizing switch during the time of starting. This eliminates a high difference of potential at the field terminals during the beginning of the starting period, and the insulation stresses are correspondingly reduced. In some cases the field circuit is short-circuited during the starting period. When the synchronous converter has nearly reached synchronous speed, the difference of potential across the d-c. brushes will slowly alternate. If the field circuit is closed when the difference of potential across the d-c. brushes is increasing with the desired polarity, the armature will lock into step and the d-c. brush polarity will be as desired. If the field circuit is not closed at the proper

time, the armature will lock into step so that the d-c. brush polarity is reversed. In that event the desired d-c. brush polarity is usually obtained in the following way: The field circuit is reversed (the field switch is usually a double-throw switch for this purpose), and this will cause the armature to slip slightly more than 90 electrical degrees and lock into step.* Then the field circuit is again reversed, and the armature will slip nearly 90 electrical degrees more and lock into step. The d-c. brush polarity will then be correct. After the proper d-c. brush polarity is obtained, the rated difference of potential is impressed across the slip rings.

Method 2. A synchronous converter may be started from the d-c. side (a suitable starting box must be used). The a-c. side is then synchronized with the a-c. supply lines. (See § 116.)

131. Voltage and current ratios for synchronous converters. With the d-c. brushes fixed on the electrical neutrals of a synchronous converter, the ratio of the effective electromotive

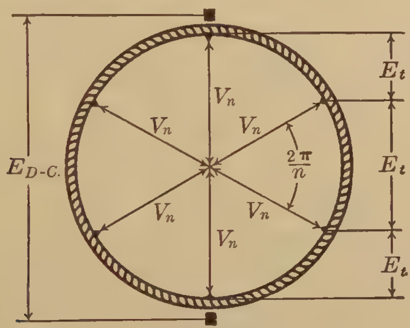

FIG. 117. An n-phase synchronous converter

force induced in the armature winding between slip rings to the electromotive force induced in the armature winding between d-c. brushes is constant, and if one is varied the other will vary correspondingly.

Fig. 117 represents an n-phase synchronous converter. The following notation is used:

$E_{d\text{-}c.}$ = electromotive force induced in the armature between brushes,

* Shepard, "Polarity Reversal in Synchronous Converters," *Electrical World*, Vol. 65 (1915), p. 210.

E_t = effective value of electromotive force induced in the armature between adjacent taps,

V_n = effective value of difference of potential between armature taps and neutral (all voltage drops in the armature are assumed to be zero)

Then $$V_n = \frac{E_{d\text{-}c.}}{2\sqrt{2}},$$

and $$E_t = 2\,V_n \sin\frac{\pi}{n} = \frac{E_{d\text{-}c.} \sin\frac{\pi}{n}}{\sqrt{2}}.$$

If the losses in an n-phase synchronous converter are neglected, and unity power factor on the a-c. side is assumed,

$$nE_t I' = E_{d\text{-}c.}\,I_{d\text{-}c.},$$

where $I_{d\text{-}c.}$ = direct current in d-c. lines,

and I' = a-c. component of current in windings.

Then $$I' = \frac{E_{d\text{-}c.} I_{d\text{-}c.}}{nE_t} = \frac{\sqrt{2}\,I_{d\text{-}c.}}{n \sin\frac{\pi}{n}}.$$

Let $I_{a\text{-}c.}$ = alternating current in a-c. lines.

Then $$I_{a\text{-}c.} = \frac{E_{d\text{-}c.} I_{d\text{-}c.}}{nV_n} = \frac{2\sqrt{2}\,I_{d\text{-}c.}}{n}.$$

The following table gives voltage and current relations for synchronous converters. It is assumed that the brushes are on the electrical neutrals, the synchronous converter losses are zero, and the power factor on the alternating-current side is unity.

Voltage and Current Relations for Synchronous Converters

Number of Armature Taps per Pair of Poles	E_t (Voltage between Adjacent Taps)	$I_{a\text{-}c.}$ (A-C. Line Current)
2 (Single phase)	$0.707\,E_{d\text{-}c.}$	$1.414\,I_{d\text{-}c.}$
3 (Three phase)	$0.612\,E_{d\text{-}c.}$	$0.943\,I_{d\text{-}c.}$
4 (Four phase)	$0.500\,E_{d\text{-}c.}$	$0.707\,I_{d\text{-}c.}$
6 (Six phase)	$0.354\,E_{d\text{-}c.}$	$0.471\,I_{d\text{-}c.}$
12 (Twelve phase)	$0.183\,E_{d\text{-}c.}$	$0.236\,I_{d\text{-}c.}$
n (n phase)	$\dfrac{\sin\frac{\pi}{n}\,E_{d\text{-}c.}}{\sqrt{2}}$	$\dfrac{2\sqrt{2}\,I_{d\text{-}c.}}{n}$

132. Ratings of synchronous converters. The current in any conductor of a synchronous-converter armature winding, when the machine is being operated under load, is made up of a component of direct current and a component of alternating current. These components of current partially cancel each other so that in polyphase synchronous converters the heating due to I^2R' loss is less than it would be if only one of the components of current were present. The heating is not the same in all of the armature conductors. When a synchronous converter is operated with unity power factor on the alternating-current side, the greatest heating will occur in the tap conductors and the minimum heating will occur in the conductors that are midway between taps. As the number of taps is increased the ratio of the maximum to minimum conductor heating becomes smaller.

It may be shown that the ratio of the outputs of a synchronous converter for equal copper losses, when first operated as an n-phase synchronous converter and then as a d-c. generator, may be expressed as follows:

$$\frac{\text{Output as an } n\text{-phase synchronous converter}}{\text{Output as a d-c. generator}} = \frac{1}{\sqrt{H}},$$

where $H = \dfrac{8}{(\text{p.f.})^2(\text{eff.})^2 n^2 \sin^2 \dfrac{\pi}{n}} + 1 - \dfrac{16}{\pi^2(\text{eff.})},$

p.f. = power factor of the synchronous converter on the a-c. side,

eff. = efficiency of the synchronous converter,

and n = number of taps per pair of poles.

The following table gives the relative outputs of an n-phase synchronous converter for equal copper losses, when it is first operated as a d-c. generator and then as a synchronous converter. Unity power factor and 100-per-cent efficiency are assumed.

SYNCHRONOUS CONVERTER OUTPUTS

	DIRECT-CURRENT GENERATOR	NUMBER OF TAPS PER PAIR OF POLES					
		$n = 2$ single phase	$n = 3$ three phase	$n = 4$ four phase	$n = 6$ six phase	$n = 12$ twelve phase	$n = \infty$
Output	1.00	0.85	1.33	1.63	1.93	2.19	2.30

The effect of lowering the power factor on the alternating-current side of a synchronous converter materially reduces its capacity, as is clearly shown in Fig. 118. The curves in the figure are based on equal copper losses and 100-per-cent efficiency.

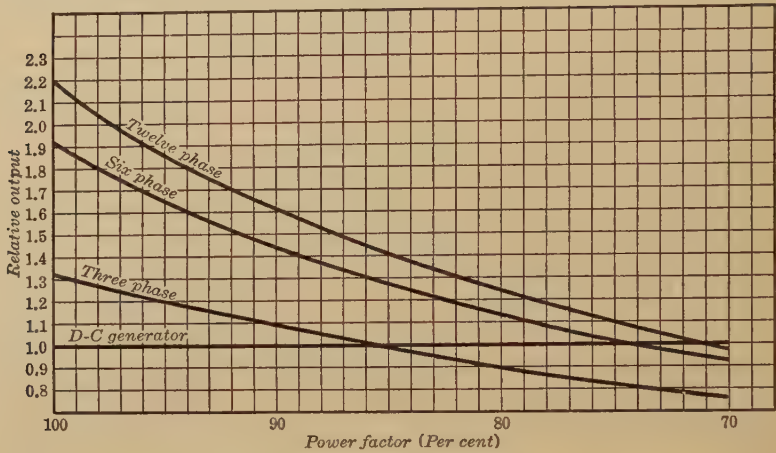

FIG. 118. Relative outputs for a synchronous converter when operating at different power factors

133. Over-speed protection for a synchronous converter. The speed of a synchronous converter, when it is being used to transform alternating current into direct current, is fixed by the number of its poles and the frequency of the a-c. supply. When the synchronous converter is being used to transform direct current into alternating current, the speed of the machine may become excessive under certain conditions. For example, when a synchronous converter is receiving power from the d-c. side and delivering power to the a-c. side, the speed of the machine may become excessive if a large inductive load is placed on the machine. An inductive load produces lagging components of alternating current in the armature conductors, and due to the fact that these lagging components of a-c. current produce a demagnetizing magnetomotive force in the armature, the field flux is reduced and the synchronous converter increases in speed. The increase in speed gives a correspondingly greater frequency on the a-c. side, and therefore the a-c. components of current in the armature conductors will lag still more. This may increase the speed still further.

When a synchronous converter is being used to supply current to storage batteries, or is being operated in parallel with other synchronous converters or direct-current generators, a short circuit on the alternating-current side of the machine will cause large lagging alternating-current components in the armature conductors. This will cause the machine to race and probably wreck itself if it is not disconnected from the d-c. lines.

It is customary to place speed-limiting devices on all synchronous converters. The speed-limiting device is attached to the synchronous-converter shaft and in the event that the speed exceeds a certain predetermined value, it operates and disconnects the synchronous converter from the d-c. lines.

EXPERIMENT 11–A

Operation of a Synchronous Converter from the Direct-Current Side

Object. To determine the operating characteristics of a synchronous converter when used for changing direct current to alternating current.

Reference. Lawrence, "Principles of Alternating-Current Machinery," Chaps. XXXVI, XXXVII, and XL.

Apparatus. A synchronous converter. A suitable source of direct current. A starting box, field rheostat, and the necessary equipment for loading the a-c. side of the converter at different power factors.

Method. 1. Start the synchronous converter as a d-c. motor. Maintain the field current constant at such a value as will give rated speed at no load. Using a dynamometer or soft-iron type of voltmeter, read the difference of potential between the various a-c. rings. Draw a diagram similar to Fig. 117. Using a dynamometer or soft-iron type and also a galvanometer type of voltmeter, take readings of the difference of potential existing between an a-c. ring and a d-c. brush.

2. Using a single-phase resistance load between diametrical taps on the a-c. side, maintain the field current and the supply difference of potential constant and vary the load by steps from zero to 150 per cent of the single-phase rating of the converter (see § 132). At each step take readings of the difference

of potential and current on both sides of the converter, the speed, field current, and power output on the a-c. side.

3. Maintain the alternating current constant at single-phase rated value. Maintain the field current constant and vary the power factor through as wide a range as possible. At each step take readings as in part 2.

4. Repeat parts 2 and 3, using a balanced polyphase load on the a-c. side.

Precautions. The converter should be equipped with an over-speed governor. Before starting the test see that this governor is in operating condition and properly adjusted. If the converter does not have an over-speed governor, be prepared to open the d-c. switch in case the speed rises abnormally. Do not allow the speed to exceed 120 per cent of rated value.

Curves. Plot the necessary curves to illustrate your results.

Questions. 1. What is the full-load rating of the converter for each of the ways in which it was used?

2. What is the nature of the current flowing in the armature coils?

3. What causes the change in speed observed?

4. How do the readings of the galvanometer and dynamometer types of voltmeters, when connected from an a-c. ring to a d-c. brush, compare with values expected from a theoretical consideration?

5. How do the observed voltage and current ratios compare with theoretical values?

EXPERIMENT 11–B

Operation of a Synchronous Converter from the Alternating-Current Side

Object. To study the operating characteristics of a synchronous converter when used for changing alternating current to direct current.

Reference. Lawrence, "Principles of Alternating-Current Machinery," Chaps. XXXVI–XXXIX.

Apparatus. A synchronous converter. A suitable source of alternating current and some means of controlling the difference of potential supplied to the a-c. side. A source of direct current

and a starting box for starting the converter from its d-c. side. Synchronizing lamps, a field rheostat, and a loading rheostat.

Method. 1. Start the synchronous converter as a d-c. motor and synchronize it with a single-phase a-c. supply. Disconnect the d-c. supply and place a loading rheostat on the d-c. side. Adjust the output to single-phase full-load value. Adjust the difference of potential on the a-c. side so as to have rated difference of potential on the d-c. side. Adjust the field current for unity power factor at full load. Maintain the field current and the difference of potential on the a-c. side constant, and vary the load on the d-c. side by steps from zero to 150 per cent of the single-phase rating of the converter (see § 132). At each step take readings of all currents and differences of potential, also power input to the a-c. side.

2. Repeat part 1 but use the converter as a polyphase converter.

3. Maintain the difference of potential supplied to the a-c. side and the current on the d-c. side constant. Vary the field current of the converter by steps through as wide a range as possible. At each step take readings as before.

4. Using about one-half normal difference of potential on the a-c. side, start the converter as an induction motor. Note the maximum current required for starting. Practice reversing the polarity of the d-c. brushes as explained in § 130.

Curves. For parts 1 and 2 plot curves of efficiency, power factor, difference of potential on the d-c. side, and line current on the a-c. side as ordinates against the current on the d-c. side as abscissas. For part 3 plot these curves against field current.

Questions. 1. What determines the speed of the synchronous converter?

2. What determines the rating of a synchronous converter?

134. Voltage control of synchronous converters. The difference of potential on the d-c. side of an ordinary synchronous converter bears a definite relation to the difference of potential on the a-c. side, and this relation cannot be changed appreciably. (The ratio of the difference of potential on the d-c. side to the difference of potential on the a-c. side will change slightly with load, due to the armature-winding impedance drop.) If the difference of potential that is supplied to the a-c. side is constant,

the difference of potential across the d-c. side of a synchronous converter may be changed by the following methods:

1. By change of slip-ring difference of potential.
   a. By means of inductive reactances placed in series with the a-c. lines.
   b. By means of an induction regulator.
   c. By means of a synchronous booster.
2. By change of wave shape.
   a. By means of split poles on the synchronous converter.

Method 1, a. Inductive reactances may be placed in series with the a-c. power supply lines that connect to the synchronous converter, in order to vary the difference of potential on the d-c. side. By over-exciting the field of the synchronous converter a leading current is drawn through the reactances, and this will produce a higher difference of potential across the slip rings. Correspondingly, a higher difference of potential is produced across the d-c. brushes. By under-exciting the field of the synchronous converter a lagging current is drawn through the reactances and a lower difference of potential is produced across the slip rings. This in turn gives a lower difference of potential across the d-c. brushes. By placing a series field on the synchronous converter it is possible to have a flat or rising voltage characteristic on the d-c. side of a synchronous converter. The series-reactance method of controlling the difference of potential on the d-c. side of a synchronous converter is simple and the first cost of the reactances is relatively small. It can produce only a limited voltage range because the difference of potential across the d-c. side cannot be changed without correspondingly changing the power factor on the a-c. side, and changing the power factor of a synchronous converter materially reduces its capacity. (See Fig. 118.)

Method 1, b. An induction regulator may be used on the a-c. side of a synchronous converter in order to vary the difference of potential on the a-c. side and, correspondingly, the difference of potential across the d-c. brushes. The first cost of a suitable induction regulator is relatively high, but this method is suitable for a wide voltage range.

Method 1, c. The synchronous-booster method consists of an ordinary synchronous converter and an alternating-current gen-

erator mounted on the same shaft. The synchronous converter and the alternator must have the same number of poles, and they must be wound for the same number of phases. One end of each phase winding of the alternator is connected to a synchronous-converter tap, and the other end of each phase winding of the alternator is connected to an a-c. power supply line. The difference of potential across the synchronous-converter taps may be varied at will by changing the field current of the alternator (booster). The difference of potential on the d-c. side will be correspondingly varied. This method of varying the difference of potential on the d-c. side of a synchronous converter is used extensively in large installations.

Method 2, a. In the split-pole method of varying the difference of potential on the d-c. side of a synchronous converter, the field poles are specially constructed. Each pole is divided into two parts parallel to the shaft. The operation of the split-pole synchronous converter depends upon the change of flux-wave shape. The electromotive force generated in the armature winding between the d-c. brushes depends upon the total lines of induction cut per pole and in no way upon the flux distribution. The effective value of the electromotive force generated in the armature winding between the slip rings is a function of the flux distribution as well as the total flux per pole. Therefore, it is possible, by properly exciting the two parts of the pole individually, to vary the electromotive force generated in the armature winding between the d-c. brushes, and keep the same effective value of electromotive force generated in the armature winding between slip rings. The ratio of the difference of potential across the d-c. brushes to the difference of potential across the slip rings is correspondingly changed.

One part of the two-part pole acts as a main pole and the other part acts as an auxiliary pole. Only the main pole is excited when the normal difference of potential on the d-c. side is desired. If a higher difference of potential is desired, the auxiliary pole is excited in the same direction as the main pole, and when a lower difference of potential on the d-c. side is desired, the auxiliary pole is excited in the opposite direction. It should be noted that the auxiliary pole is not an interpole.

The split-pole method of varying the difference of potential on the d-c. side of a synchronous converter is used but little.

EXPERIMENT 11–C

The Compounding of a Synchronous Converter

Object. To study the effect of compounding on the voltage regulation and power factor of a synchronous converter.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. L.

Apparatus. A synchronous converter having a series field winding. A suitable source of a-c. supply and some means of controlling the supply difference of potential. Suitable inductive reactances for inserting in the a-c. lines to the synchronous converter. The necessary auxiliary equipment for starting and loading the synchronous converter.

Method. 1. Determine the operating characteristics of the synchronous converter when using the series field but without series reactances in the a-c. lines. Maintain the difference of potential of the a-c. supply constant at such a value as to produce rated difference of potential on the d-c. side at full load. Maintain the shunt-field current constant at such a value as will produce unity power factor at full load. Vary the load on the converter, by steps, from zero to a safe overload. At each step take readings of the differences of potential, currents, and power on the a-c. side, the difference of potential, load current, and field current on the d-c. side.

2. Insert equal amounts of inductive reactance in each of the a-c. leads. Again maintain the supply difference of potential constant, vary the load, and take readings as in part 1. In addition take readings of the supply difference of potential and the drop of potential through each reactance coil.

3. Adjust the value of the reactances in the a-c. leads or the ampere-turns of the series field so that the synchronous converter will be flat-compound. Take a set of readings as in part 2.

Curves. For each of the three sets of readings, plot curves of efficiency, power factor, differences of potential of the d-c. and a-c. sides as ordinates against the current on the d-c. side as abscissas.

Question. What are the advantages and disadvantages of this method of voltage control as compared with other methods

of controlling the difference of potential on the d-c. side of a synchronous converter?

135. Mercury-vapor rectifier. The mercury-vapor rectifier, in the smaller sizes, consists of a specially constructed glass bulb as shown in Fig. 119. All gases except mercury vapor have been exhausted from the bulb and the pressure of the mercury vapor will be extremely small. There are two anodes or positive terminals and they are labeled *A* and *A′*. These terminals are usually made of graphite. In the bottom of the bulb there are

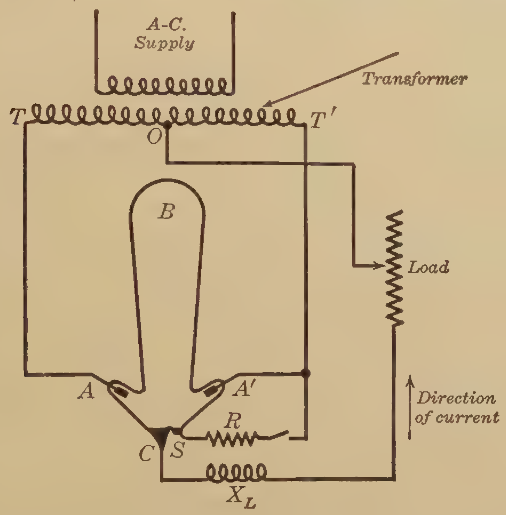

FIG. 119. Single-phase mercury-vapor rectifier

two pools of mercury. The larger pool is the cathode or negative terminal. The smaller mercury pool is used for starting purposes. When the rectifier is in operation, mercury vapor is formed and it rises in the large upper space of the bulb. This large upper space acts as a cooling chamber, so that the mercury vapor condenses on the glass and runs in droplets back to the cathode. A large cooling chamber is essential for the successful operation of a mercury-vapor rectifier. Otherwise the mercury vapor that is produced by the passage of electricity from the anodes to the cathode would not condense at a high enough rate to keep the mercury-vapor pressure within the bulb at a sufficiently low value.

If the surface temperature of the mercury pool (the cathode) is high, a current of electricity will pass through the bulb from either anode to the cathode with a comparatively small difference of potential (from 14 to 25 volts, with A or A' positive and C negative) across the terminals. This may be explained as follows: When the mercury surface is at a high temperature, large numbers of free electrons are emitted from it. If one of the anodes is positive while the cathode is negative, and if the difference of potential between the anode and cathode is above the critical value, these emitted electrons move in a direction from the cathode to the anode with considerable velocity. These electrons traveling at high velocities collide with the atoms of mercury vapor. As a result of these collisions, electrons are detached from the mercury-vapor atoms in such large numbers that the total free electrons become many times greater in number than they would be if the difference of potential between the anode and cathode were below the critical value. When a neutral mercury-vapor atom is deprived of one or more electrons it is positively charged, and it is called a positive ion. The positive ions move toward the cathode in a stream and bombard the surface of the mercury pool, and keep it heated to a high temperature. The positive ions are continually recombining with the free electrons so that the total number of positive ions as well as the total number of electrons is constant for a given current and difference of potential between the anode and cathode. The bulb acts like a valve and even with the mercury-surface temperature very high it would require several thousand volts to send an appreciable current through the bulb from the cathode to either anode.

The high mercury-surface temperature that is necessary for operation is obtained, when starting, by tilting the bulb so that the mercury in the pools completes an electrical circuit, and then tipping the bulb back. When the bulb is returned to its normal position, the "mercury switch" breaks and an arc is formed. This arc produces the necessary high mercury-surface temperature at the cathode.

The operation of the mercury-vapor rectifier, after starting, may be explained as follows: Let it be assumed that the mercury-surface temperature is maintained at a high value by some means. When A is positive with respect to C and the difference of

potential from A to C reaches the critical value, current will flow through the bulb from A to C and on through the load. As soon as the difference of potential between A and C drops below the critical value, the current will reduce to zero. After a short interval of time the alternating difference-of-potential wave will pass through zero and, for the next half cycle, A' will be positive with respect to C. When the difference of potential between A' and C reaches the critical value, current will flow through the bulb from A' to C and on through the load. After a short interval of time this current will reduce to zero due to the difference of potential between A' and C dropping below the critical value. The alternating difference-of-potential wave will again pass through zero, and A will become positive with respect to C. This cycle of events will repeat itself indefinitely. It will be noted that the current through the load circuit is unidirectional, and it varies from zero to a maximum and then back to zero. In the commercial mercury-vapor rectifier a reactance is placed in series with the load circuit, and in Fig. 119 this reactance is labeled X_L. The reactance has the property of opposing any change of current in the load circuit, so that the load current will not reduce to zero at any time while the mercury-vapor rectifier is in operation. In other words, the unidirectional current may be represented by a continuous-current component plus an alternating-current component, and the maximum value of the alternating-current component is less than the continuous-current component. If the load current is not allowed to reach relatively low values at any time, the mercury-surface temperature will keep sufficiently high for operation, and no other special equipment except the reactance will be necessary. The mercury-vapor rectifier will not operate if the minimum value of the load current becomes too low, unless other special arrangements are made for keeping the mercury-surface temperature high. For example, an artificial load could be used, but this would lower the efficiency of the mercury-vapor rectifier considerably.

The difference of potential across the d-c. load is changed by properly adjusting the difference of potential on the a-c. side of the mercury-vapor rectifier. The connection at O must be kept at a point midway between T and T'. Due to the fact that the critical voltage necessary to operate the bulb is very nearly

constant regardless of load or the alternating difference of potential used, the ratio of the unidirectional difference of potential to the alternating difference of potential between T and O is not a fixed value. The unidirectional difference of potential will always be less than the maximum value of the alternating difference of potential between T and O.

The power loss in the bulb is directly proportional to the current, as the drop in the bulb (critical voltage) is practically

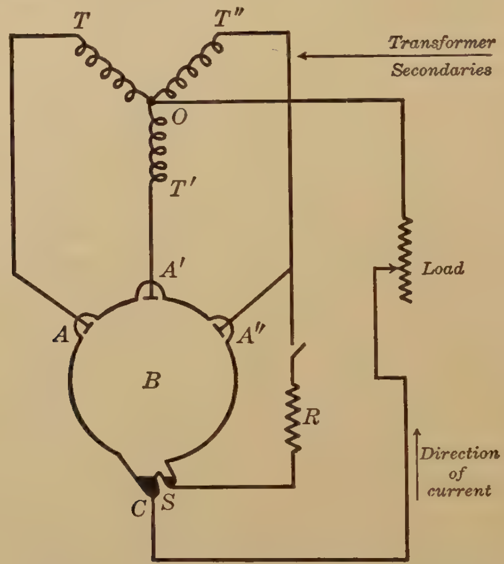

FIG. 120. Three-phase mercury-vapor rectifier

constant. Therefore the efficiency of the mercury-vapor rectifier is a function of the unidirectional difference of potential. The higher the unidirectional difference of potential, the higher the efficiency will be. The power factor on the a-c. side is reasonably high.

The three-phase mercury-vapor rectifier is shown in Fig. 120. At least one of three anodes will be positive with respect to the cathode, and for ordinary operation the difference of potential between one positive anode and the cathode will be greater than the critical value. Therefore a reactance in series with the load is not necessary except for smoothing out the unidirectional current wave.

In the large-size mercury-vapor rectifiers the glass bulb is replaced with a steel casing. A water-cooling system is arranged for cooling the steel casing and the anodes. Three, six, and sometimes twelve phases are used in the large-size mercury-vapor rectifiers. Increasing the number of phases gives a greater output for a given size of steel casing and a smaller difference between the maximum and minimum values of the unidirectional current. The transformer is connected delta on the primary and three-phase, six-phase, or twelve-phase star on the secondary. Polyphase mercury-vapor rectifiers may be

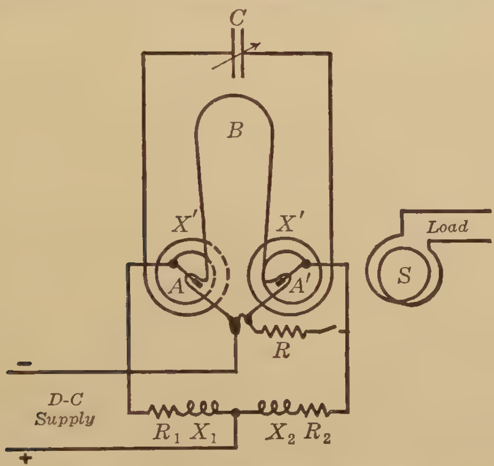

FIG. 121. The Vreeland oscillator

operated in parallel. They are being used to a considerable extent in automatic as well as manually operated substations. They have a relatively high efficiency. They do not need to be synchronized and, consequently, may be put into service in a few seconds. Three standard sizes are made for electrical railway substations that give 300, 600, and 1000 amperes at 600 volts.

The mercury-vapor rectifier may be used for transforming direct current into alternating current. When the mercury-vapor rectifier is used in this way it is called a Vreeland oscillator.* A diagram of connections for a Vreeland oscillator is shown in Fig. 121, where R_1 and R_2 are like resistances, and X_1

* *Physical Review*, Vol. 27 (1908), p. 286.

and X_2 are like reactances. When the oscillator is operating, two arc streams carry the current from the anodes to the cathode. The two coils, X', are placed about the bulb in such a manner that their magnetic field will deflect the double arc stream toward one or the other of the anodes. The frequency of the alternating electromotive force induced in the load circuit will depend upon the constants of the circuit, and the frequency may be varied from 250 to 2500 cycles per second. The frequency is usually varied by changing the capacity of the condenser C. The output of the Vreeland oscillator is limited to a few watts, but the alternating induced electromotive force in the load circuit is a pure sine wave.

EXPERIMENT 11-D

The Mercury-Vapor Rectifier

Object. To study the operating characteristics and determine the performance curves of a mercury-vapor rectifier.

Reference. Karapetoff, "Experimental Electrical Engineering," Chap. LXII.

Apparatus. A mercury-vapor rectifier. A suitable source of alternating current and some means of maintaining constant supply difference of potential. A loading rheostat.

Method. 1. Study the operating instructions furnished by the manufacturer for the particular rectifier to be used in this experiment. The student should familiarize himself with the starting and control equipment and practice starting the rectifier several times.

2. Maintain the supply difference of potential constant at rated value and vary the direct current, by steps, from full load to as low a value as will maintain the arc in operation. At each step take readings of the power lost in the bulb itself, also the current, power input, and difference of potential on the a-c. side. On the d-c. side use both galvanometer and dynamometer types of instruments and take readings of the average and effective values of the current and difference of potential.

3. Insert a high inductive reactance in series with the load and observe the minimum value of current which will maintain the arc in operation.

4. Maintain the supply difference of potential constant at rated value and the direct current constant at some value near full load. Vary the difference of potential on the d-c. side, by means of the control equipment, through as wide a range as possible and, at suitable intervals, take readings as in part 2.

5. Using an oscillograph, observe or photograph the various current and voltage waves.

Curves. Plot the performance curves of the mercury-vapor rectifier.

Questions. 1. How does the addition of reactance in the load circuit affect the minimum value of current which will maintain the arc in operation?

2. What is the shape of the wave of the difference of potential between one anode and the cathode?

3. In large mercury-vapor rectifiers it is necessary to water-cool the steel casing and the anodes. Why is it not necessary to water-cool the cathode?

136. Frequency converters. The most common form of frequency converters is the commutator machine. The commutator on a direct-current generator simply changes the alternating current in the armature windings to zero-frequency current (direct current) in the line. The commutator on the rotor of the brush-shifting polyphase induction motor (explained in § 123) converts currents of line frequency into currents with the slip frequency of the secondary. Other examples of the commutator-type frequency converters may be cited.

Synchronous motor-generator sets are commonly used for changing frequencies from 25 cycles to 60 cycles or vice versa in large power systems.

The wound-rotor polyphase induction motor may be used as a frequency converter. When the polyphase induction motor is so used the load is connected to the rotor terminals. The rated frequency and difference of potential are impressed across the stator terminals, and the rotor is driven by some electric motor or prime mover. The rotor frequency may be varied from zero to twice the rated frequency of the induction motor without exceeding a speed that is numerically equal to the synchronous speed. If the rotor is driven in the direction of the rotating

magnetic field the rotor frequency will be less than the stator frequency, and at synchronous speed the rotor frequency will be zero. At standstill the rotor frequency will be equal to the frequency of supply to the stator of the induction motor. When the rotor is driven against the direction of the rotating magnetic field the rotor frequency will be greater than the stator frequency, and at a speed that is numerically equal to the synchronous speed the rotor frequency will be two times the frequency that is being supplied to the stator.

It will be necessary to absorb power mechanically from the rotor when it is driven below synchronous speed, when driven in the direction of the rotating magnetic field, except for speeds very near synchronous speed. When the rotor is rotated against the rotating magnetic field, mechanical power must be supplied to the rotor.

The electromotive force generated in the rotor is proportional to the frequency of the rotor.

The rotor iron losses are a function of the rotor frequency, so they must be taken into consideration when loading the induction motor as a frequency converter. It may be necessary to reduce the rotor output current to a value below the normal full-load value of the rotor in order to avoid overheating the rotor when the rotor frequency is more than a few per cent of the applied stator frequency.

137. Single-phase-to-polyphase converters. Polyphase synchronous or induction motors may be used for single-phase-to-polyphase converters. A motor, in order that it may be used as a single-phase-to-polyphase converter, must be wound for the same number of phases as are desired on the polyphase side of the converter, or in such a manner that in combination with transformers it may be used for supplying power with the desired number of phases. When only single-phase power is available, it will be necessary to resort to some method of single-phase starting. (See §§ 121 and 122 for an induction motor and § 118 for a synchronous motor.) After the motor is running and receiving power from the single-phase side, polyphase power may be supplied to a load from the machine. The motor should have no mechanical load attached if the greatest polyphase output is desired. The principal objection to the induction-type single-phase-to-polyphase converter is that its power factor on

the single-phase side is inherently lower than that of the synchronous-type converter. The synchronous-type converter permits of power-factor adjustment on the single-phase side.

Synchronous single-phase-to-polyphase converters are used in the electric locomotives on the Norfolk and Western Railroad in Virginia. Single-phase power is supplied to the locomotive by way of the overhead trolley, and three-phase motors are used for driving the locomotive. The single-phase-to-polyphase converter serves as a connecting link between the single-phase power supply and the three-phase motors. A small single-phase starting motor is mounted on the shaft of the converter. An earlier form of single-phase-to-polyphase converter used in electric locomotives on this railroad was of the induction type.

APPENDIX A

TREATMENT FOR ELECTRICAL SHOCK*

An accidental electrical shock usually does not kill at once, but may only stun the victim and for a while stop the breathing.

The shock is not likely to be immediately fatal, because:

1. The conductors may make only a brief and imperfect contact with the body.

2. The skin, unless it is damp with perspiration or wet, offers some resistance to the current.

The life of the victim depends upon the prompt and continued use of artificial respiration. The reasons for this are:

1. The body continuously depends on an exchange of air, as shown by the fact that we must breathe in and out about fifteen times a minute.

2. If the body is not thus repeatedly supplied with air, suffocation occurs.

3. Persons whose breathing has been stopped by electrical shock have been reported restored after artificial respiration has been continued for approximately four hours, and the treatment should be continuously applied until rigor mortis (stiffening of the body due to death) sets in.

The Schaefer, or "Prone-Pressure," method of artificial respiration, slightly modified, is illustrated and described in the following resuscitation rules. The advantages of this method are:

1. It is immediately available.

2. Easy performance; no apparatus and little muscular exertion required.

3. Larger ventilation of the lungs than by the supine method.

4. Simplicity: the operator makes no complex motions and readily learns the method.

5. No trouble from the tongue falling back into the air passages. The first impulse is expiration and any foreign substance in the mouth or air passage will probably be expelled.

6. No risk of injury to the liver or ribs if the method is executed with proper care.

Aid can be rendered best by one who has studied the rules and has learned them by practice on a volunteer subject.

* Issued by the National Electric Light Association.

INSTRUCTIONS FOR RESUSCITATION

Follow These Instructions Even if Victim Appears Dead

I. Free the Victim from the Circuit Immediately

1. Quickly release the victim from the current, being very careful to avoid receiving a shock. Use any dry non-conductor (rubber gloves, clothing, wood, rope, etc.) to move either the victim or the conductor. Beware of using metal or any moist material. If both of the victim's hands are grasping live conductors, endeavor to free them one at a time. If necessary shut off current.

Begin at once to get the subject to breathe (resuscitation), for a moment of delay is serious. Use "Prone-Pressure Method" for four (4) hours if necessary, or until a doctor has advised that rigor mortis has set in.

Observe the following precautions:

a. The victim's loose clothing, if dry, may be used to pull him away; do not touch the soles or heels of his shoes while he remains in contact — the nails are dangerous. If this is impossible, use rubber gloves, a dry coat, a dry rope, a dry stick or board, or any other *dry non-conductor* to move either the victim or the conductor, so as to break the electrical contact.

b. If the bare skin of the victim must be touched by your hands, be sure to cover them with rubber gloves, mackintosh, rubber sheeting or dry cloth; or stand on a dry board or on some other dry insulating surface. If possible, use only *one* hand.

If the man receives a shock while on a pole, first see that his belt is secure around the pole, if possible above cross arm so victim will not fall, then break the current. Pass a hand-line under his arms, preferably through his body belt, securely knot it, and pass the end of the line over the first cross arm above the victim. If you are alone, pass the line once around this cross arm. If you are not alone, drop the line to those at the base of the pole. As soon as the rope is taut, free the victim's safety belt and spurs and descend the pole, guiding the victim.

2. Open the nearest switch, if that is the quickest way to break the circuit.

3. If necessary to cut a live wire, use an ax or a hatchet with a dry wooden handle, turning your face away to protect it from electrical flash.

II. Attend Instantly to Victim's Breathing

1. As soon as the victim is clear of the live conductor, quickly feel with your finger in his mouth and throat and remove any foreign

body (tobacco, false teeth, etc.). If the mouth is tightly shut, pay no attention to the above-mentioned instructions until later, but immediately begin resuscitation. The patient will breathe through his nose and after resuscitation has been carried on a short time, the jaws will probably relax, and any foreign substance in the mouth can then be removed. Do not stop to loosen the patient's clothing; *every moment of delay is serious.*

2. Lay the patient on his belly, one arm extended directly overhead, the other arm bent at the elbow and with the face resting on hand or forearm so that the nose and mouth are free for breathing. (See Fig. 1.)

FIG. 1

3. Kneel, straddling the patient's hips, with the knees just below the patient's hip bones or opening of pants pockets. Place the palms of the hands on the small of the back with fingers resting on the ribs, the little finger just touching the lowest rib, the thumb alongside of the fingers, the tips of the fingers just out of sight. (See Fig. 1.)

4. With arms held straight, swing forward slowly so that the weight of your body is gradually brought to bear upon the subject (see Fig. 2). This operation, which should take from two to three seconds, *must not be violent* — internal organs may be injured. The lower part of the chest and also the abdomen are thus compressed, and air is forced out of the lungs, the diaphragm is kept in natural motion, other organs are massaged, and the circulation of the blood accelerated.

5. Now *immediately* swing backward so as to completely remove the pressure, thus returning to the position shown in Fig. 3. Through their

FIG. 2

FIG. 3

elasticity, the chest walls expand, and the pressure being removed the diaphragm descends, and the lungs are thus supplied with fresh air.

6. After two seconds swing forward again. Thus repeat deliberately twelve to fifteen times a minute the double movement of compression and release — a complete respiration in four or five seconds. If a watch or a clock is not visible, follow the natural rate of your own deep breathing; the proper rate may be determined by counting — swinging forward with each expiration and backward with each inspiration.

7. As soon as this artificial respiration has been started and while it is being continued, an assistant should loosen any tight clothing about the patient's neck, chest, or waist. *Keep the patient warm.* Place ammonia near the nose, determining safe distance by first trying how near it may be held to your own. Do not give any liquids whatever by mouth until the patient is fully conscious.

8. Continue artificial respiration without interruption (if necessary, for four hours) until natural breathing is restored. Cases are on record of success after three and one-half hours of effort. The ordinary tests for death are not conclusive in cases of electric shock and doctors must be so advised by *you*, if necessary.

9. When the patient revives, he should be kept lying down and not allowed to get up or be raised under any consideration unless on the advice of a doctor. If the doctor has not arrived by the time the patient has revived, he should be given some stimulant, such as one teaspoonful of aromatic spirits of ammonia in a small glass of water, or a drink of hot ginger tea or coffee.

The patient should then have any other injuries attended to and be kept warm, being placed in the most comfortable position.

10. Resuscitation should be carried on at the nearest possible point to where the patient received his injuries. He should not be moved from this point until he is breathing normally of his own volition, and then moved only in a lying position. Should it be necessary, due to extreme weather conditions, etc., to move the patient before he is breathing normally, he should be kept in a prone position and placed upon a hard surface (door or shutter) or on the floor of a conveyance, resuscitation being carried on during the time that he is being moved.

11. A brief return of spontaneous respiration is not a certain indication for terminating the treatment. Not infrequently, the patient, after a temporary recovery of respiration, stops breathing again. The patient must be watched, and if normal breathing stops, artificial respiration should be resumed at once.

III. Send for a Doctor

If other persons are present when an accident occurs, send one of them for a doctor without a moment's delay. If alone with the patient, do not neglect the immediate and continued resuscitation of the patient for at least one hour before calling a doctor to assist in further resuscitation efforts.

IV. First Care of Burns

When natural respiration has been restored, burns, if serious, should be immediately attended to while waiting for the doctor to arrive.

A raw or blistered surface should be protected from the air. If clothing sticks, do not peel it off — cut around it. The adherent cloth, or a dressing of cotton or other soft material applied to the burned surface, should be saturated with picric acid (0.5 per cent). If this is not at hand, use a solution of baking soda (one teaspoonful to a pint of water), or the wound may be coated with a paste of flour and water, or it may be protected with vaseline, carron oil, olive oil, castor oil, or machine oil if clean. Cover the dressing with cotton, gauze, lint, clean waste, clean handkerchief, or any other soft cloth, held tightly in place by a bandage.

The same coverings should be lightly bandaged over a dry, charred burn, but without wetting the burned region or applying oil to it.

Do not open blisters.

APPENDIX B

TABLE I. PROPERTIES OF STANDARD ANNEALED COPPER WIRE

A.W.G. Number	Diameter in Mils	Area in Cir. Mils	Weight in Pounds		Resistance at 20° C. (68° F.)	
			1000 ft.	Mile	1000 ft.	Mile
0000	460.0	211,600.	640.5	3,382.	.049 0	.259
000	409.6	167,806.	507.9	2,682	.061 8	.326
00	364.8	133,077.	402.8	2,127.	.077 9	.411
0	324.9	105,535.	319.5	1,687.	.098 3	.519
1	289.3	83,692.7	253.3	1,338.	.123 9	.654
2	257.6	66,371.3	200.9	1,061.	.156 3	.825
3	229.4	52,634.8	159.3	841.2	.197 0	1.040
4	204.3	41,741.3	126.4	667.1	.248 5	1.312
5	181.9	33,102.4	100.2	529.1	.313 3	1.654
6	162.0	26,251.4	79.46	419.6	.395 1	2.086
7	144.3	20,818.3	63.02	332.7	.498 2	2.630
8	128.5	16,509.7	49.97	263.9	.628 2	3.317
9	114.4	13,092.8	39.63	209.3	.792 1	4.182
10	101.9	10,383.0	31.43	165.9	.998 9	5.274
11	90.74	8,234.11	24.92	131.6	1.260	6.650
12	80.81	6,529.95	19.77	104.4	1.588	8.386
13	71.96	5,178.48	15.68	82.77	2.003	10.57
14	64.08	4,106.72	12.43	65.64	2.525	13.33
15	57.07	3,256.78	9.858	52.05	3.184	16.81
16	50.82	2,582.74	7.818	41.28	4.016	21.20
17	45.26	2,048.21	6.200	32.74	5.064	26.74
18	40.30	1,624.30	4.917	25.96	6.385	33.71

TABLE II. CURRENT-CARRYING CAPACITY

A.W.G. Number	Diameter of Solid Wires in Mils	Area in Cir. Mils	Rubber Insulation, Amperes	Varnished-Cloth Insulation, Amperes	Other Insulation, Amperes
18	40.3	1,624	3		5
16	50.8	2,583	6		10
14	64.1	4,107	15	18	20
12	80.8	6,530	20	25	25
10	101.9	10,383	25	30	30
8	128.5	16,510	35	40	50
6	162.0	26,251	50	60	70
5	181.9	33,102	55	65	80
4	204.3	41,741	70	85	90
3	229.4	52,635	80	95	100
2	257.6	66,371	90	110	125
1	289.3	83,693	100	120	150
0	324.9	105,535	125	150	200
00	364.8	133,077	150	180	225
000	409.6	167,806	175	210	275
		200,000	200	240	300
0000	460.0	211,600	225	270	325
		250,000	250	300	350

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